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TECHNICAL MEMORANDUM 1307

LATERAL CONTROL BY SPOILERS AT THE DVL

By M. Kramer, Th. Zobel, and C. G. Esche

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By M. Kramer, Th. Zobel, and C. G. Esche

I. SYSTEMATIC WIND-TUNNEL TESTS CONCERNING THE PROBLEM OF LATERAL CONTROL BY SPOILERS PERMEABLE TO AIR

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By C. G. Esche

PREFACE

The present report describes the development of spoiler control at the DVL during the period from the end of 1936 until the beginning of 1939. The authors are fully aware that the present report also forms only a contribution to the problem of spoiler control and offers at best a possibility of extrapolation regarding the behavior of the control in modern airplanes. A modern airplane (Me 109) is being reconstructed for conversion to spoiler control. Experience has shown, however, that the construction and testing of such a model requires at least a year. Thus it seems appropriate to report summarily now in order to keep the understanding and cooperation of the interested departments aroused. The following reports are only a section of a long development partly evolved abroad. For that reason, we shall first present a survey of the total problem.

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*"DVL - Unterbrecherquersteuerung." Zentrale für wissenschaftliches Berichtswesen bei der Deutschen Versuchsanstalt für Luftfahrt, E. V. (ZWB) Berlin-Adlershof, Forschungsbericht Nr. 964, July 13, 1938 - May 24, 1938 - May 13, 1939

The origin of lateral control by spoiler goes back to the time when the Handley-Page-Lachmann lateral slotted-wing control was developed in England. The first spoilers served to interrupt on one side the flow at the slot of the slotted wing in order to support the effect of the ailerons at high lifts. The surprisingly large rolling effectiveness of these spoilers led to making tests also with spoilers without slotted wings. The most intensive and extensive tests of this type were performed by the American, Weick, and his co-workers during the years 1930 to 1933. He varied height, length, and rearward position of the spoiler and used, in addition to simple plates, also wide-toothed forms. For his flight tests, he found the time lag of spoilers by which is meant the lag between movement of the control surface and the response of the airplane. He proved that the time lag for sufficiently effective spoilers becomes intolerably large in practice; since he could not find a suitable expedient for reducing this lag, he finally discontinued the tests with simple spoilers. In the following years, Weick developed lateral control by means of a slot-lip aileron, a combination of a spoiler with a slot; that arrangement is free from lag, but came to be used only for slow airplanes because of the profile disruption by the open slot far out in front.

In 1936, the suggestion was made at the DVL that the spoiler be provided with a finely distributed screen-like permeability, and that a counter spoiler be arranged on the pressure side of the profile.[1] The permeability was to diminish the time lag, the counter spoiler was to increase the effectiveness in high-speed flight and simultaneously to reduce the inconveniently large positive yawing moments. A preliminary test in the small wind tunnel of the DVL confirmed the basic feasibility of that suggestion (FB 583). Therefore, an extensive investigation of the problem was started in the large wind tunnel of the DVL; somewhat later, construction of a test airplane was decided upon.

The test in the large wind tunnel again confirmed the effectiveness shown in the preliminary test. Beyond that, it provided data concerning suitable permeability, height, length, and rearward position of the permeable spoiler and of the counter spoiler. The result was that usable rolling and yawing moments in the entire flight range could be attained as well as a noticeable reduction of the time lag. The results of the wind tunnel test were taken into account in the construction of the test airplane.

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[1]This suggestion as well as the later one regarding the spoiler with lead spoiler was made by M. Kramer - DVL.

An airplane model (Fieseler "Storch") was selected as test airplane which was particularly well suited for the measurement of time lag due to small wing loading (about 50 kg/m^2) and rectangular wing contour. The test flights showed that even with a permeable spoiler the time lag, at least for the wing loading of the test carrier, was still inadmissibly large. Although it must be taken into consideration that spoiler control, fundamentally, is destined for airplanes with high wing loading and trapezoidal wings and that the lag decreases in inverse proportion to the wing loading and with approximately the fourth root of the taper, it seemed, nevertheless, expedient to look for ways and means of reducing the lag still further.

Thus in 1938, it was suggested that the spoiler be divided into a lead spoiler and a main spoiler. The lead spoiler was to be a spoiler with very high permeability and particularly high control speed, thus to show particularly small lag aerodynamically and mechanically whereas the main spoiler would reduce the permeability of the lead spoiler and thus produce the lower permeability required for attainment of a sufficient effectiveness.

This suggestion was first examined mathematically and then tried out in flight tests. However, it became clear that various inadequacies had to be accepted due to the fact that the lead spoiler had been installed later; these inadequacies prevented an exact checking of the lead spoiler on the first test carrier. Checking of this suggestion must therefore be left to the second test airplane (Me 109) being built at present.

By extrapolating the results existing so far to 150 kg/m^2 wing loading and a taper of about 1/3, one obtains for maximum lift a lag of only about 1/4 that of the values measured on the "Storch." One may assume that such slight lags become permissible in practice. However, the final decision in this respect depends solely on the flight test with the second test airplane now under construction which is not to serve for measurement of the aerodynamic effect, like the "Storch," but for testing of the spoiler under the conditions for which it is actually meant.

PART I. SYSTEMATIC WIND-TUNNEL TESTS CONCERNING THE PROBLEM OF LATERAL CONTROL BY SPOILERS PERMEABLE TO AIR

By M. Kramer and Th. Zobel

Abstract: The present report describes the continuation of the experiments started at the beginning of 1936 on spoilers permeable to air. The measurements that have now been carried out systematically on a modern wing in the large wind tunnel of the DVL confirm and broaden the result of the preliminary test formerly described. We succeeded in approximating to a great extent the rolling effectiveness of the permeable spoiler to that of standard lateral control and in making the yawing moment for the former even more favorable than for the latter. Besides, the permeable spoiler reduces the time lag of standard spoiler control to about one half. Since, however, a time lag still exists, the efforts toward its reduction are not terminated with this report, and the possibility of practical use of spoiler control is not yet guaranteed.

Outline:

I. INTRODUCTION
II. TEST SETUP, MEASURING METHOD, AND TEST PERFORMANCE
III. DISCUSSION OF THE RESULTS OF THE NONSTATIONARY MEASUREMENTS
IV. DISCUSSION OF THE RESULTS OF THE STATIONARY MEASUREMENTS
V. SUMMARY
VI. REFERENCES

I. INTRODUCTION

Modus operandi and properties of standard lateral control by means of ailerons, its advantages and defects, are sufficiently known (reference 1). Its insufficient effectiveness in badly stalled flight and its reducing of the span disposable for landing flaps led to the development of a lateral control by means of spoiler flaps. Flight tests (references 2 and 3) have proved that lateral control by spoilers improves effectiveness in stall, but shows, on the other hand, two fundamental defects which so far have prevented its practical use, namely:

(1) Large time lag, that is, delay between control deflection and response

(2) Large positive yawing moments which cause inconveniently strong yawing during the rolling motion

Various investigations have been carried out with the purpose of reducing the time lag of spoilers; negligibly small lags resulted when spoilers in connection with a slot (reference 5), with the standard aileron or with a second spoiler (arranged behind the first one but near the wing trailing edge) were used (reference 2). However, such methods do not yet represent satisfactory solutions since the reduction in time lag is attained at the price of accepting other disadvantages, for instance, drag increase in high-speed flight or limitation of the landing-flap length.

Within the scope of the American flight tests for improvement of spoiler control (reference 2), a partition of the spoiler surface into several spoiler elements also was investigated. The type used was a saw-tooth spoiler, toothed over a distance equal to the spoiler height, with the basis of the triangular spoiler elements touching the wing surface. The American report did not lead to a clear verdict as to whether or not an improvement is obtainable by a partition of the spoiler because - as was found out afterwards - the comparison had been decisively disturbed by the use of different amounts of wing dihedrals. Weick himself assumed that no improvement is attained by the saw-tooth. Anyway, this report contains the essential sentence: "It was suggested that with a saw-tooth spoiler, instead of the air being deflected upward from the wing, turbulence might be set up by the sides of the teeth and that this turbulent flow might pass directly along the wing surface and cause more rapid distruction of the lift."

At the beginning of 1936, fundamental spoiler tests in the wind tunnel were started at the DVL (reference 1). Weick's saw-tooth was checked; no improvement was found to result. Independent of the checking of the saw-tooth, tests with screen-type spoilers were made at the time on the hypothesis that the important thing ought to be production of a flow as homogeneous as possible behind the spoiler. (It was then already known that only very slight turbulence promotes adherence of a flow, whereas rough turbulence furthers separation). The test with screen-type spoilers actually resulted in a considerable improvement of the spoilers with respect to time lag as well as with respect to the ratio of variation in lift to variation in drag (rolling moment/yawing moment). Therefore, the defects of the preliminary test were eliminated (small characteristic value, indirect measurement of the lag), the field systematically investigated, and the new results compiled in the present report.

II. TEST SETUP, MEASURING METHOD, AND TEST PERFORMANCE

The tests were carried out in the large wind tunnel (5 × 7 m) of the DVL at 50 meters per second jet velocity (R = 2,450,000) on the wing model (fig. 1) of a tested type. The model had a span of 5 meters elliptical wing contour, and was provided with differential aileron control without slot and with landing flaps situated on the inside. Ailerons and landing flaps could be rigged up when necessary at angles of attack up to 70° so that a landing flap extending over almost the entire span was produced. All of the various spoilers used for the investigation could be deflected only at a distance of 20 percent of the wing chord from the wing nose.

In a preliminary test on a small model in which the influence of rearward position and height of the spoiler and of its spanwise extent on the rolling moment were determined, the distance of 20 percent length proved advantageous in agreement with the results of other reports (references 1 and 4). With increasing distance, the rolling moment of the spoiler decreases considerably at large angles of attack. At a distance of 50 percent l, it amounts to only about half the value attained for 20 percent l.

Spoilers deflected on the pressure side of the opposite wing at the same distance from the wing leading edge augment the rolling moment in the range of high-speed flight, do not affect it for medium c_a-values, and reduce it for large c_a-values by only a small amount. By further rearward placement of the spoiler on the pressure side, this reduction of the rolling moment can be avoided in low-speed flight. However, further rearward placement on the pressure side was not examined more thoroughly since it involves the danger of a disturbance to the landing flap lying behind it.

An increase in height of the spoiler beyond 5 percent causes, for a permeable spoiler, only a relatively small growth of the rolling moment and a rapid drag increase, whereas the impermeable spoiler permits heights up to about 7 percent. An increase in the length of the spoiler proved suitable for balancing the reduced effect of the permeable spoiler due to decreased height. As to the structural dimensioning of permeable spoilers, a height of 5 percent l and a length of 50 percent B/2 was shown to be a favorable value for the production of sufficient rolling moments. All permeable spoilers used within the scope of the present investigation had been dimensioned to this size. Their rolling moment corresponded in magnitude on the average to that of a solid spoiler of h = 7 percent l and b = 30 percent B/2 such as had already been used in flight tests at the DVL (reference 3) whence it was included for comparison.

In practical flight, criticism has to be applied regarding the usefulness of lateral control by spoilers derived from the time lag on one hand, from the reciprocal action of rolling and yawing motion on the other. For the wind-tunnel test, in contrast, one arrives at an approximate statement regarding the usability of such a control type by separately carrying out nonstationary measurements of the time lags and stationary measurement of the rolling and yawing moments and discussing the results obtained in connection with one another.

For the nonstationary measurements of the variation with time of the air forces on the wing in case of abrupt spoiler deflection, unequivocal measurement of the short-term time lag and a recording, as free from inertia as possible, were required. This requirement was met by the installation of a DVL Ritz device in one of the two lift balances. On the same side of the balance were the spoilers which could be deflected by means of an electromagnet (fig. 2) within the short time of 1/30 second. Considerable experimental difficulties had to be surmounted before faultless Ritz recordings could be achieved. For the purpose of increasing the natural frequency of the wing, the customary initial tension of the model suspension was omitted in the measurement.

The lag between completion of the control deflection and attainment of the full static rolling moment was defined as the measure of the time lag of the lateral control. This lag t_v could be taken in each case from the Ritz recordings in which the course of the lift forces on the wing was plotted against the time (figs. 3 and 4).

The aileron used for the comparative measurements could be deflected within the same control time of 1/30 second. Such short times of actuation were chosen in order to avoid as far as possible the effect of unavoidable differences in the time required for control upon the variation of forces on the wing.

For sudden deflection of the spoilers, the measurements were initially impeded by the fact that strong fundamental wing oscillations were excited by the hard impact of the accelerated mass on the limiting deflection which rendered the Ritz recordings less evaluable. However, this difficulty was eliminated by light construction of the spoilers and of the supporting device and by suitably damped limiting deflection so that Ritz recordings which could be evaluated unequivocally and reproduced at any time could now be made (figs 3 and 4); they permitted a measuring accuracy of about 1/100 second.

With these presuppositions regarding measuring technique, the following permeable spoilers of different types (fig. 5) were investigated, in addition to the standard aileron and a solid spoiler (already used in previous flight tests) of h = 7 percent l and b = 30 percent $B/2$,

the rolling effectiveness of which was found to be sufficient:

(1) Screen-type spoilers with uniform drag distributions, but different degrees of permeability; Nos. 1, 2, 3, and 9 (fig. 5)

(2) Screens, the solidity of which decreases in the direction of the height of the spoiler; Nos. 4, 5, and 6 (fig. 5)

(3) Perforated plates, the solidity of which decreases in the direction of the height of the spoiler; Nos. 7 and 8 (fig. 5)

(4) Rake-type spoilers with different permeabilities and two different ratios between rake spacing and height; Nos. 1 to 3 (fine-toothed), Nos. 4 to 6 (wide-toothed) (fig. 5)

The two last types, 3 and 4, have been investigated in regard to the practical construction since screens are probably unsuitable in this respect. Type 4 of the rakes appears to be particularly promising; it has - provided that aerodynamical equivalence to the screens or perforated plates exists - the operational advantage of being able to eventually project through a row of holes in the wing skin and thus only partially to disrupt the torsional unity of the wing.

Measurements of the time lags were made for three different c_a-values, 0.18, 0.5, and 1.0, of the undisturbed smooth wing corresponding to the angles of attack of 2°, 7°, and 15°. Three Ritz recordings were made at each angle of attack and the time lags thus obtained were averaged.

In order to throw light also on the time lags in case of application of landing flaps extending over the entire span, the flaps together with the ailerons were deflected 70° and the spoiler effect was superimposed on this arrangement.

III. DISCUSSION OF THE RESULTS OF THE NONSTATIONARY MEASUREMENTS

In previous investigations regarding the serviceability of spoilers as lateral control, it was found that the rolling and yawing moments could be varied and controlled within wide limits with comparatively simple expedients, whereas the elimination of time lags offered considerable difficulties. In spite of the fact that spoilers are in various respects superior to ailerons, lateral control by spoilers is so far not yet ready for practical use because of the still existing time lag;

this lag deprives the pilot of "feel" and very considerably impedes warding of gusts as well as safe maneuvering of the airplane.

Figure 6 shows the measured time lags of the various spoilers and of the aileron plotted over c_a. The permeable spoilers show on the average time lags amounting to about one-half or one-third those of the solid spoiler - the first in low-speed flight, the latter in high-speed flight. In contrast, the aileron operates practically free from inertia, that is, with the beginning of the aileron deflection the rolling moment increases and attains its stationary value as soon as the aileron is fully deflected. Figures 3 and 4 show four such Ritz recordings of spoilers and ailerons and illustrate the basic difference in the modus operandi of the two types of lateral control Evaluation of the Ritz recordings offered first of all a synopsis of the time lags attained with various spoilers and of the lift reduction in each case; only the promising spoilers were selected and with them exact static measurements of the rolling and yawing moments were performed with the balance.

It is noteworthy in figure 6 that the wider-toothed rakes (nos. 4 to 6) show less favorable results throughout regarding their time lag than the geometrically similar rakes of finer spacing (Nos. 1 to 3). This fact proves again (reference 1) why the American tests with a saw-tooth spoiler could not succeed. What is of importance is actually the production of a homogeneous, slightly turbulent flow behind the spoiler. If the turbulence exceeds a critical value, separation occurs again and the time lags increase.

Figure 7 represents the rolling-moment coefficients of these spoilers over the time lags measured at three different c_a-values (c_a = 0.18, 0.5, and 1.0). If curves are drawn through the measuring points of the individual permeable spoilers for equal c_a-values (fig. 8), the rolling moments are found to be increasing with the solidity of the screens (higher c_{w_S}-values). (c_{w_S} is the drag coefficient of a screen measured in a pipe from the pressure drop.) With growing c_{w_S}-values the time lags also increase. The rolling moments, however, do not increase linearly with the solidity of the spoilers, but obey another law. They tend toward a terminal value not much higher than the rolling-moment value attained with screens of average c_{w_S}-values (about 2.0). To illustrate this fact, the approximate rolling-moment coefficients of the solid spoiler ($c_{w_S} = \infty$) of the same structural dimensions (h = 5 percent l and b = 50 percent B/2) as all permeable spoilers have been calculated from the lift reduction in the Ritz recordings and also plotted, in dashed lines, in figure 8.

A very interesting behavior is shown by the perforated plate 7, the c_{w_S} of which decreases in case of standard arrangement (fig. 5)

in the direction of the spoiler height. If this perforated plate is used turned around so that the more permeable part is placed next to the wing, the rolling moment is, in case of high c_a-values, reduced only slightly, the time lag, however, to almost one-half. In high-speed flight, the behavior of such an arrangement is of course very unfavorable because the reduction in time lag is linked with a simultaneous intolerable loss in rolling moment of about 1/3 of the original value.

The behavior of the perforated plate 7 shows that modification of the c_{ws} in direction of the spoiler height results even in the most favorable case only in time lags which coincide with the limiting curve of simple screen-type spoilers. This fact shows that such a special construction is not superior to ordinary permeable spoilers with uniform drag distribution. The only way left for further reducing the lags is to use permeable spoilers of smaller c_{ws} and to augment the rolling moment to the required value by increasing the span portion, since according to experience, the time lags of a permeable spoiler are not affected by modification of its length. With these expedients, however, one approaches closely the maximum permissible design length of about 70 percent B/2 without attaining a very considerable gain in time lags.

A phenomenon observed for rapid deflection of the spoilers in American measurement (references 2 and 5) as well as in flight tests of the DVL should be pointed out. The spoiler on the suction side of the wing generally causes, after the deflection, a lift reduction and therewith a rolling moment. The latter, however, does not immediately start acting in the proper sense; there occurs, on the contrary, at first a lift increase that rotates in flight the wing in the opposite sense. In the first phase of the spoiler deflection, the air apparently passes over the obstacle without causing the flow to separate, and the effect of an increase in camber and thus an increase in lift is produced. Only for larger spoiler deflection the spoiler then acts as separation flap, and the lag is terminated only when the dead air space behind the spoiler is fitted in up to the full wing chord.

At first it seemed likely that the lift increase at the start of the spoiler deflection could occur only in case of extendable front-hinged spoilers. In such an arrangement, the spoiler forms - at a small deflection angle - a slender wedge over which the flow passes without separating so that the effect which is that of an increase in camber is understandable. However, tests showed that the same phenomenon could be observed for rear-hinged spoiler flaps and for spoilers that could be extended from slots in the wing. For a prescribed rearward position of the spoiler, this undesirable effect could be eliminated by a permeable spoiler. In case of a solid spoiler, however, that effect disappears only if the spoiler is placed toward the rear.

For the conversion of the time lags t_v determined in the wind-tunnel tests to the conditions of actual flight, the dynamic characteristics S (reference 6) must be taken into account as well as the Reynolds number. In suitable transformation, the dynamic characteristic is

$$S = \frac{l}{vt_v}$$

t_v = time lag

l = mean wing chord at the position of the spoiler

v = flight velocity

whence it follows that the variation in time lag in actual flight is proportional to the wing chord and inversely proportional to the flight speed. If rolling acceleration and therewith the rolling moment are measured in the flight test, the results are - on the basis of the above consideration - comparable, if the effect of the moment of inertia on the time lag and, furthermore, the variation of the rolling moment during the motion are neglected. The time lag in flight then is

$$t_{v\ \text{flight}} = t_v \frac{l_{\text{flight}}}{l_{\text{model}}} \frac{v_{\text{model}}}{v_{\text{flight}}}$$

And since the model measurement had shown the values $l = 0.77$ meter and $v = 50$ meters per second, there results for the evaluation of the measuring results

$$t_{v\ \text{flight}} = t_v \frac{50}{0.77} \frac{l_{\text{flight}}}{v_{\text{flight}}} = 65\ t_{v\ \text{model}} \frac{l_{\text{flight}}}{v_{\text{flight}}}$$

Figure 9 shows the time lags converted to the conditions in flight for a Messerschmitt M 27. The results of the DVL flight tests of Esche-Ahlborn (thinly drawn) have been included for comparison.

Consideration of the time-lag coefficient permits, moreover, the important conclusion that the pointed wing is superior to the rectangular wing with respect to time lag since, for customary tapers, the mean wing chord at the location of the spoiler is noticeably smaller than the corresponding value for rectangular wings. That means that the rectangular wing is appropriate for the investigation of the lag effects which are not readily measurable. For the practical application of spoilers, however, the trapezoidal wing is the only one in question as long as difficulties regarding lag exist.

Since the spoiler, insofar as it is satisfactory as a lateral control, enables the use of landing aids, such as landing flaps or Fowler flaps, along the entire span and thus offers a valuable increase in maximum lift, the tests were carried out also in that direction. Figure 10 shows that the time lags for deflected landing flaps and

permeable spoilers in low-speed flight (which is the flight speed of importance here) are on the average 0.07 second, and thus almost equal to the time lag for a wing without landing flaps, whereas the time lag for the solid spoiler is about 50 percent greater. In this case, too, the time lags for aileron are practically equal to zero.

In a comparison of time lags in wind tunnel tests with time lags as determined in flight tests, great caution is advisable because different definitions of time lags appear in the literature. In the flight test results published so far, the rolling velocity was always plotted against time, and "time lag" denotes the time from start or completion of the aileron deflection to the start of the rolling motion in the proper sense; in wind tunnel tests, on the other hand, the time lag was defined as the time from completion of the aileron deflection to attainment of the full static rolling moment.

In American flight tests, the fact was ascertained that a time lag of 0.1 second which was recorded by the measuring instruments can no longer be felt or observed by the pilot and that this amount of time lag represents approximately the permissible limiting value. In the application of this figure, too, caution is advisable if it is to be used in connection with the results of wind-tunnel tests because this time lag is measured from the start of aileron deflection to the start of rolling motion and indicates that for the control time of the aileron control of 0.2 second, which is here in use, the rolling motion sets in when the spoiler is only half-way deflected.

The existing time lag measurements indicate the limiting conditions which, converted to conditions of flight, can be attained with permeable spoilers used as a lateral control. However, only flight tests can decide whether or not these time lags are tolerable.

IV. DISCUSSION OF THE RESULTS OF THE STATIONARY MEASUREMENTS

Since so far no general criterion for the required effectiveness of a lateral control exists, the standard aileron is almost always dimensioned with regard to sufficient effect in low-speed flight, except when the airplanes have a special purpose of application. However, here too the aileron dimensioning is based on purely empirical values. It is therefore expedient to make a comparison of various lateral controls on the basis of sufficient rolling effectiveness in low-speed flight and to choose, for instance, the following basis of comparison: Two lateral controls are to be denoted as equivalent with regard to their rolling effectiveness when the static rolling moments produced by full aileron deflection at $c_{a\ max}$ of the smooth wing are of equal magnitude. (It

must be noted in this comparative consideration that the wing model used corresponds to a practically tested construction type of satisfactory maneuverability.)

The condition named above can be satisfied by appropriate dimensioning of the spoilers. Beyond that, however, there exists a fundamental difference in the modus operandi of the two lateral-control types. Whereas for the aileron of standard construction the rolling-moment coefficient remains almost unchanged in the entire flight range up to high c_a-values, the rolling-moment coefficient of spoiler control decreases with increasing velocity. Since, for constant rolling-moment coefficient, the rolling velocity increases proportionally to the flight velocity, the standard lateral control which is dimensioned for sufficient rolling effectiveness in low-speed flight is, as a rule, overdimensioned in high-speed flight, particularly so because of today's large velocity range high-speed flight landing. Thus, a reduction of the effect in high-speed flight, such as exists automatically when a spoiler is used, is not necessarily a disadvantage.

Figures 11 and 19 show the variation of the rolling-moment coefficients of the different lateral-control arrangements over the angle of attack. One can see that a permeable spoiler which reduced the time lags of the solid spoiler of $h = 7$ percent l and $b = 30$ percent $B/2$ to about one-half attains, with the dimensioning of $h = 5$ percent l and $b = 50$ percent $B/2$, the rolling effectiveness of the aileron at $c_{a\ max}$, especially when continuous landing flaps are used.

Whether or not the reduced effectiveness of the spoiler in high-speed flight is a disadvantage must be decided for the individual case. Figure 15 shows that counteracting arrangement of permeable spoilers on both sides (screen 9) makes it possible to increase the rolling effectiveness of the spoiler in high-speed flight by about 100 percent without having to accept a considerable loss in rolling moment in low-speed flight (aside from other advantages which will be discussed later).

If one furthermore considers the fact that the spoiler deflection reduces the damping-in-roll of the wing by 20 to 30 percent (for deflection on both wing panels even up to 50 percent) which in the end increases the efficiency of the spoiler, the results warrant the conclusion that the rolling effectiveness of permeable spoilers can be adapted to that of standard lateral control.

Aside from the rolling effectiveness, the yawing moment occurring in control actuation is of importance for judging various lateral controls. The yawing-moment coefficients of the different lateral controls are plotted over the angle of attack in figures 12 and 16. (The moment coefficients are in this report referred to the coordinate system fixed

relative to the flight path, and to the entire span). Since, however, the absolute values of the yawing moments are insignificant and it is only their relation to respective rolling moment which characterizes the quality of the lateral control, the ratio c_{mS}/c_{mq} has been plotted in figures 14 and 18.

One recognizes from these figures the well-known behavior of the standard differential aileron control, which shows practically no yawing moment in high-speed flight, comparatively small negative yawing moments in low-speed flight, and such pronouncedly negative (thus sideslip-promoting) yawing moments in stall that experienced pilots forego the use of the aileron in badly stalled flight and rather keep the machine horizontal by means of the rudder.

In contrast, the solid spoiler (fig. 14) produces in high-speed flight enormous positive yawing moments which attain the magnitude of the rolling moment and are certainly inadmissible; permeability of the spoiler greatly improves this behavior and produces practically admissible results in individual cases. In stall, that is, the range where the standard aileron fails, the solid spoiler produces positive yawing moments of noteworthy magnitude whereas the permeable spoiler shows only small positive moments. Considering the fact that both spoilers show, in the range of stall, greater rolling effectiveness than the aileron and that positive yawing moments are a safeguard against sideslip, one may conclude that the behavior of the permeable spoiler in low-speed flight approximately represents the desirable ideal which is superior to the behavior of standard lateral control and aids in reducing the danger of sideslip still looming large today, which cannot be counteracted by aileron control.

In high-speed flight, the behavior of standard lateral control is fully satisfactory so that any deviation from it in high-speed flight very probably leads to a deterioration. Using the results of the preliminary test (reference 1), we therefore arranged spoilers also on the pressure side of the wing which could be actuated in the opposite sense. These spoilers corresponded exactly to the spoilers used in each case on the suction side.

Figure 18 shows that the c_{mS}/c_{mq} behavior of the spoilers is favorably influenced by the spoilers on the pressure side and that the permeable spoiler now for actuation on both sides in the opposite sense in high-speed flight corresponds exactly to the behavior of standard lateral control. Since the fact that the permeable spoiler in low-speed flight is presumably superior to standard lateral control has been motivated before, it now follows that the permeable spoiler actuated on both sides is fully satisfactory with respect to its static behavior, and that it probably even will alleviate the disadvantages of standard lateral control in low-speed flight.

In order to attain, finally, a synopsis of the serviceability of lateral control by spoilers in case of use of landing flaps over the entire span, we deflected the landing flaps as well as the ailerons used as landing flaps and investigated this arrangement with spoilers and ailerons. With the spoilers, the landing-flap deflections were:

1. $\beta_L = \beta_Q = +70^\circ$, in addition spoiler screen I

2. $\beta_L = 70^\circ$, $\beta_Q = 35^\circ$, in addition spoiler screen I

With the aileron

1. $\beta_L = 70^\circ$, $\beta_Q = 35^\circ$ as landing flap, in addition, ailerons at $+10^\circ$ and -30° so that the total twist amounts to $+45^\circ$ and $+5^\circ$

2. $\beta_L = 70^\circ$, $\beta_Q = 15^\circ$ as landing flap, in addition, ailerons at $+23^\circ$ and -30° so that the total twist amounts to $+38^\circ$ and -15° (Positive sign before the control surface deflections signifies increase in lift.)

The results of the measurements with landing flaps are given in figures 19 to 21. Utilization of landing flaps along the entire span with use of spoilers produces a 13 percent increase in $c_{a\ max}$ compared to the wing (fig. 21) with landing flaps and standard lateral control where the aileron can be dropped as a landing flap only up to a small angular deflection of 15°. For the aileron rigged as landing flap at 30° angle of attack and superimposed aileron deflection of the standard magnitude $+23^\circ$ and -30°, the rolling effectiveness in low-speed flight - the only type of flight to be discussed for full landing-flap deflection - decreases to about one half. Permeable spoilers produce, for full landing-flap deflection of 70° over the entire span, a very good rolling effectiveness and are equivalent to the optimum aileron arrangement with $\beta_L = 70^\circ$ and $\beta_Q = +38, -15^\circ$. The solid spoiler considered for comparison gives, as in all previous rolling-moment measurements, values lower by about 10 percent than the permeable spoilers. The behavior of the spoilers regarding their yawing moments is not considerably affected by the deflection of the landing flaps.

V. SUMMARY

For thorough study of a previous fundamental preliminary test (reference 1) spoilers permeable to air on a modern wing were systematically investigated in the large DVL-wind tunnel, and compared with known lateral controls. The results were, in detail:

Using an appropriate degree of permeability (c_{w_S} = 2.0) and a counter spoiler on the pressure side of the wing moving upward, one succeeds in closely simulating the rolling effectiveness of standard lateral control. The superiority in stall is maintained (fig. 15).

The same measures (permeability c_{w_S} = 2.0 and counter spoiler) lead to such favorable equalization conditions of the yawing moments that in this respect the spoiler appears to be superior to standard lateral control (fig. 18).

The main defect of standard spoiler control, the time lag, is not completely eliminated by the introduction of permeability. For the permeability which results in satisfactory rolling effectiveness (c_{w_S} = 2.0), the time lag is reduced to one-half for high c_a-values, to about one-third for small c_a-values (fig. 8). It is necessary to keep on working on the problem of time lag in order to attain in this respect also a fully satisfactory behavior.

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2. Weick, Fred E., Soulé, Hartley A., and Gough, Melvin N.: A Flight Investigation of the Lateral Control Characteristics of Short Wide Ailerons and Various Spoilers with Different Amounts of Wing Dihedral. NACA Rep. 494, 1934.

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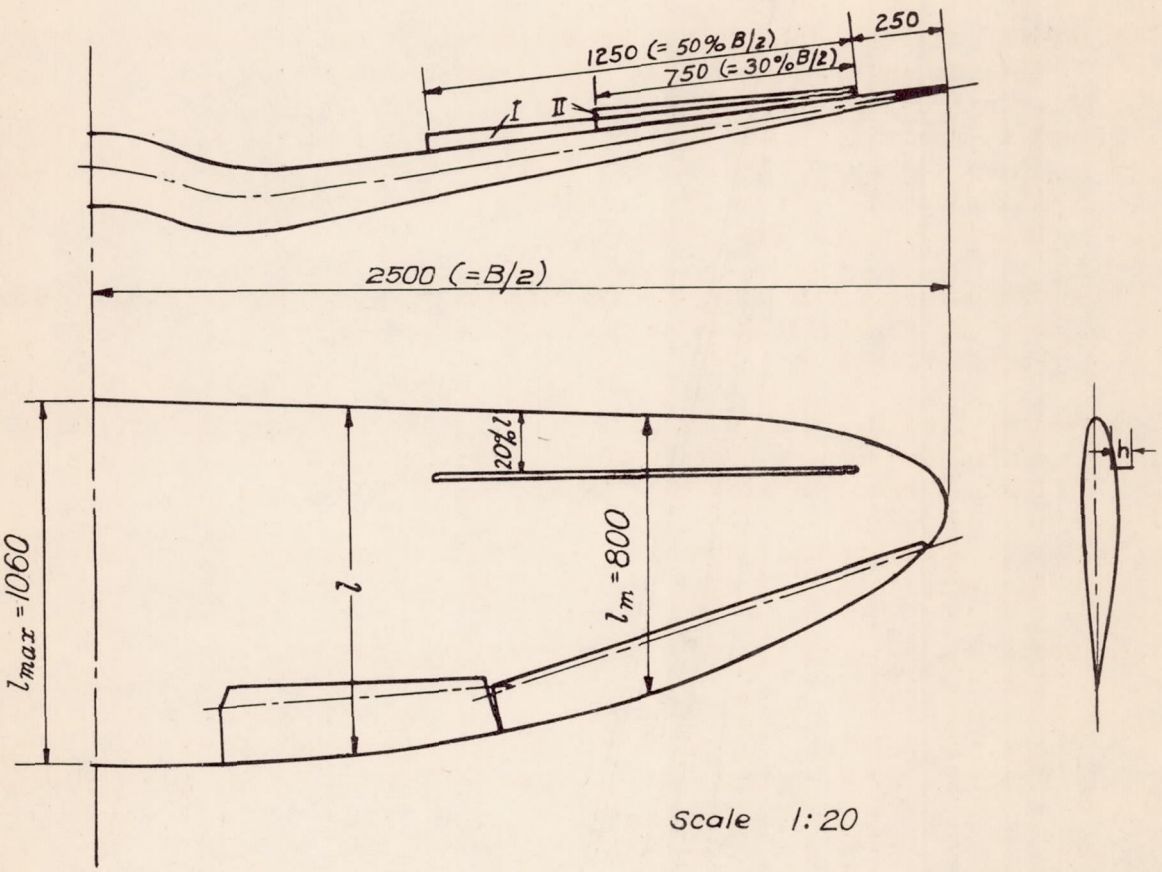
7. Jones, B. Melvill: Dynamics of the airplane. Vol. V of "Aerodynamic Theory", W. F. Durand, ed., Julius Springer (Berlin) 1935, p. 83.



I Permeable spoiler $h = 5\% l$
II Solid spoiler $h = 7\% l$

l = wing chord (mm)
l_{max} = wing chord at wing root
l_m = wing chord at center of spoiler

Figure 1.- Model wing with spoiler and aileron.

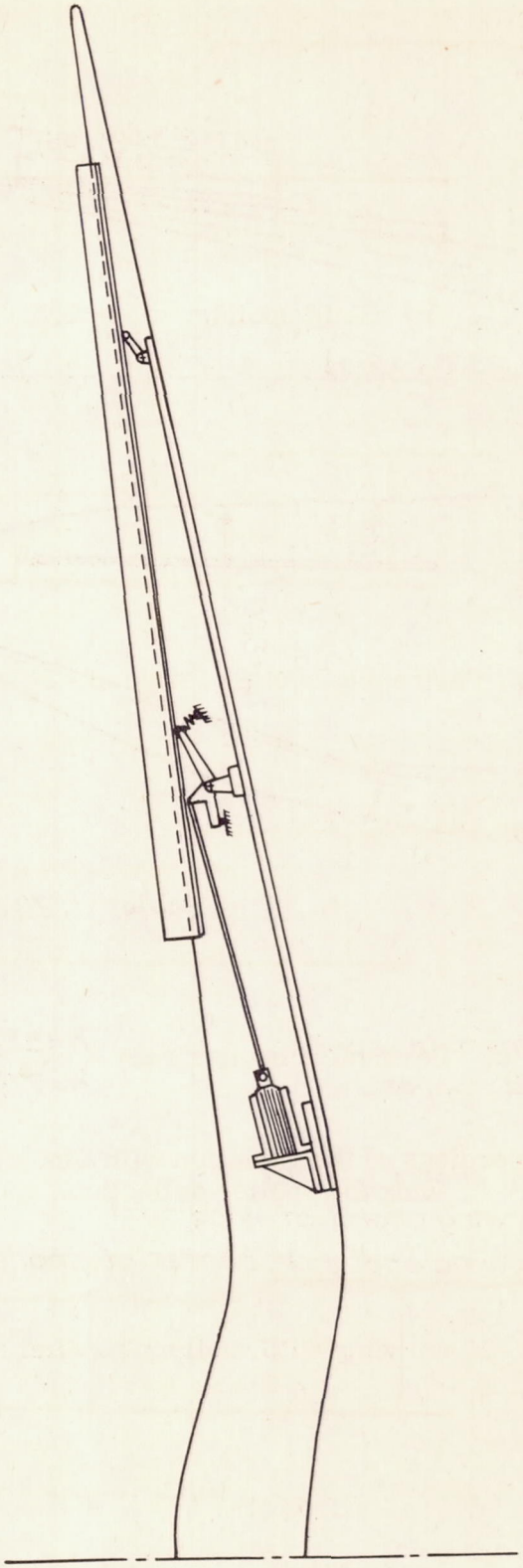
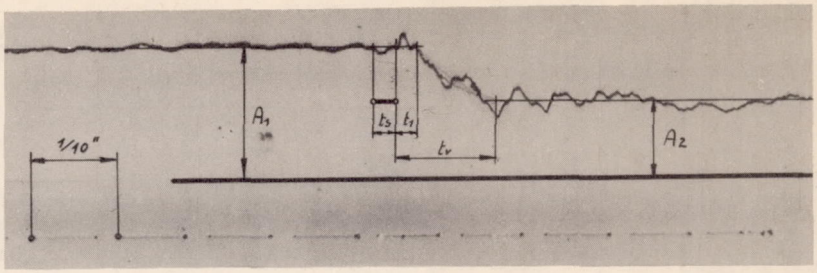
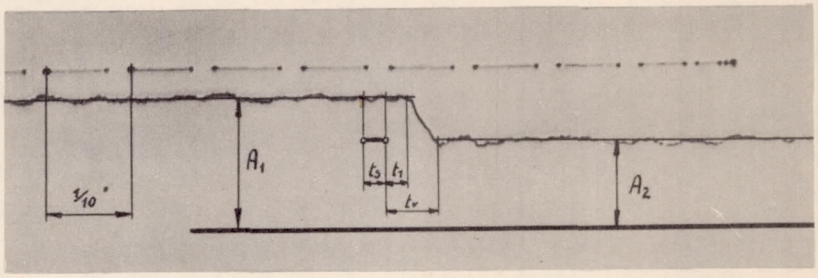


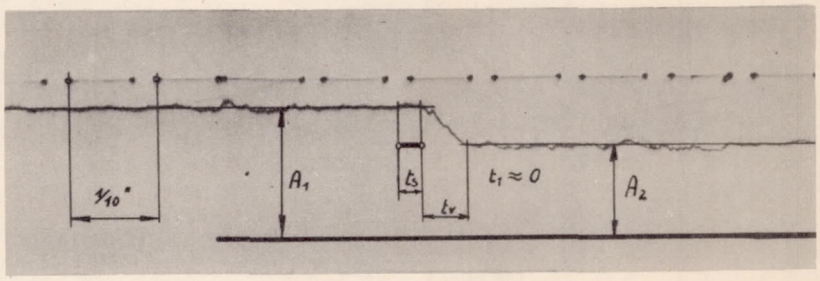
Figure 2.- Wing with spoiler and deflection mechanism.



(a) Solid spoiler; $c_a = 1.0$.

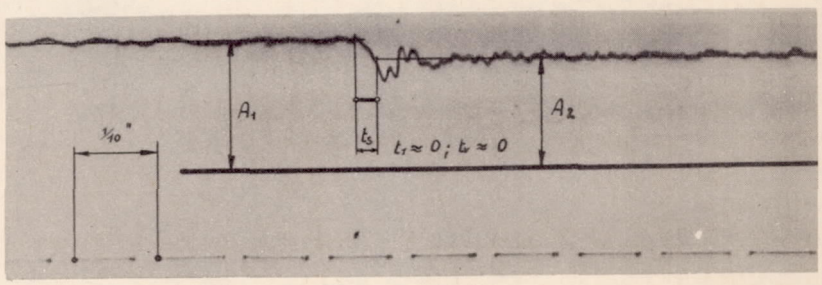


(b) Permeable spoiler screen 9; $c_a = 1.0$.



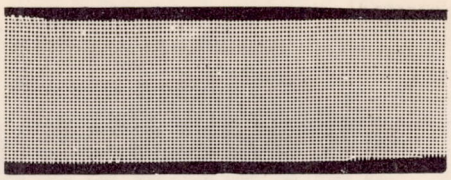
(c) Permeable spoiler rake 2; $c_a = 1.0$.

Figure 3.- Ritz recordings of the variation with time of the lift forces at the wing for spoiler deflection.

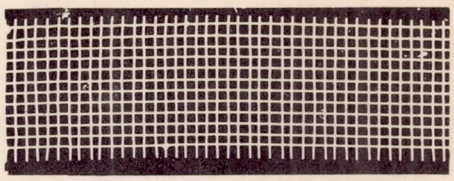


Aileron; $c_a = 1.0$.

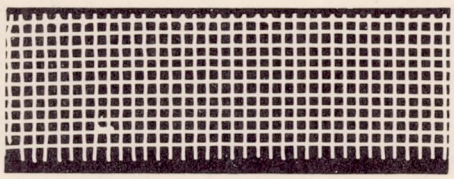
Figure 4.- Ritz recordings of the variation with time of the lift forces at the wing for aileron; $c_a = 1.0$.



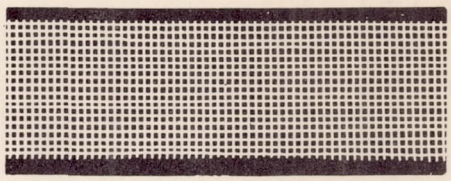
Screen No. 1
$c_{w_S} \cong 2.00$



Screen No. 2
$c_{w_S} = 00.65$

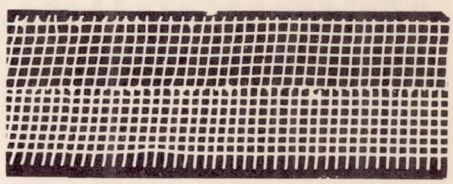


Screen No. 3
$c_{w_S} = 1.12$

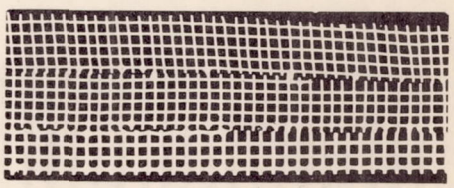


Screen No. 9
$c_{w_S} = 2.2$

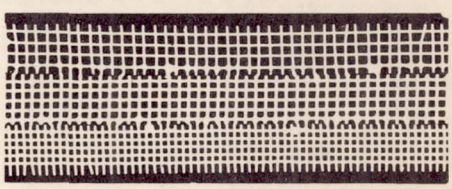
Screen No. 4 $c_{w_S} = \begin{matrix} 0.65 \\ 1.20 \end{matrix}$

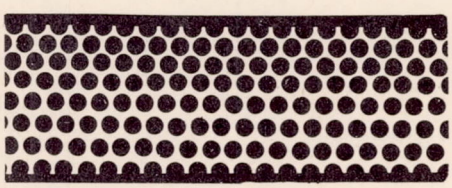


Screen No. 5 $c_{w_S} = \begin{matrix} 0.65 \\ 0.70 \\ 1.12 \end{matrix}$

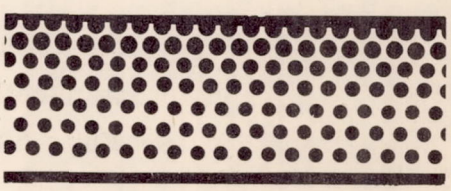


Screen No. 6 $c_{w_S} = \begin{matrix} 0.65 \\ 1.20 \\ 2.20 \end{matrix}$



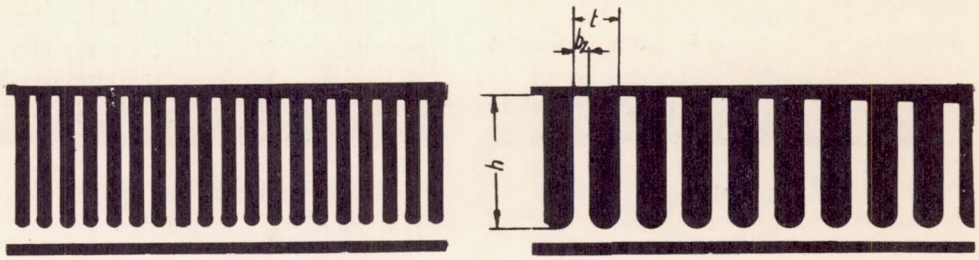


Perforated plate No. 7



Perforated plate No. 8

Figure 5.- Permeable spoilers of different construction types and permeabilities (scale of figure, 1:2.2, full scale).

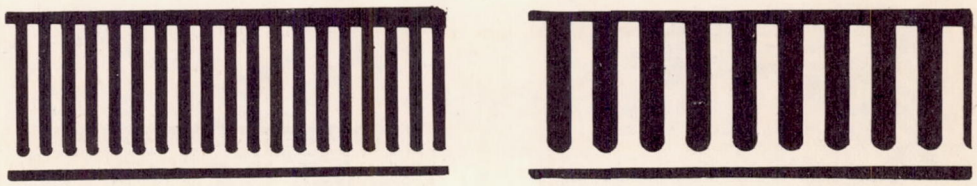


Rake No. 1

$\frac{b_z}{t} = \frac{3}{8}; \frac{h_m}{t} = 4.4$

Rake No. 4

$\frac{b_z}{t} = \frac{3}{8}; \frac{h_m}{t} = 2.2$

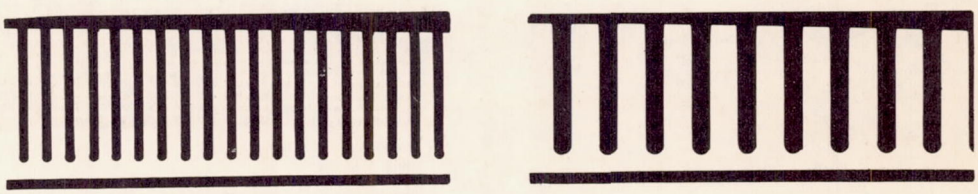


Rake No. 2

$\frac{b_z}{t} = \frac{4}{8}; \frac{h_m}{t} = 4.4$

Rake No. 5

$\frac{b_z}{t} = \frac{4}{8}; \frac{h_m}{t} = 2.2$



Rake No. 3

$\frac{b_z}{t} = \frac{5}{8}; \frac{h_m}{t} = 4.4$

Rake No. 6

$\frac{b_z}{t} = \frac{5}{8}; \frac{h_m}{t} = 2.2$

b_z = tooth width = 3, 4, 5, 6, 8, and 10 mm

h_m = mean tooth height = 35 mm

t = spacing = 8 and 16 mm

Figure 5.- Concluded.

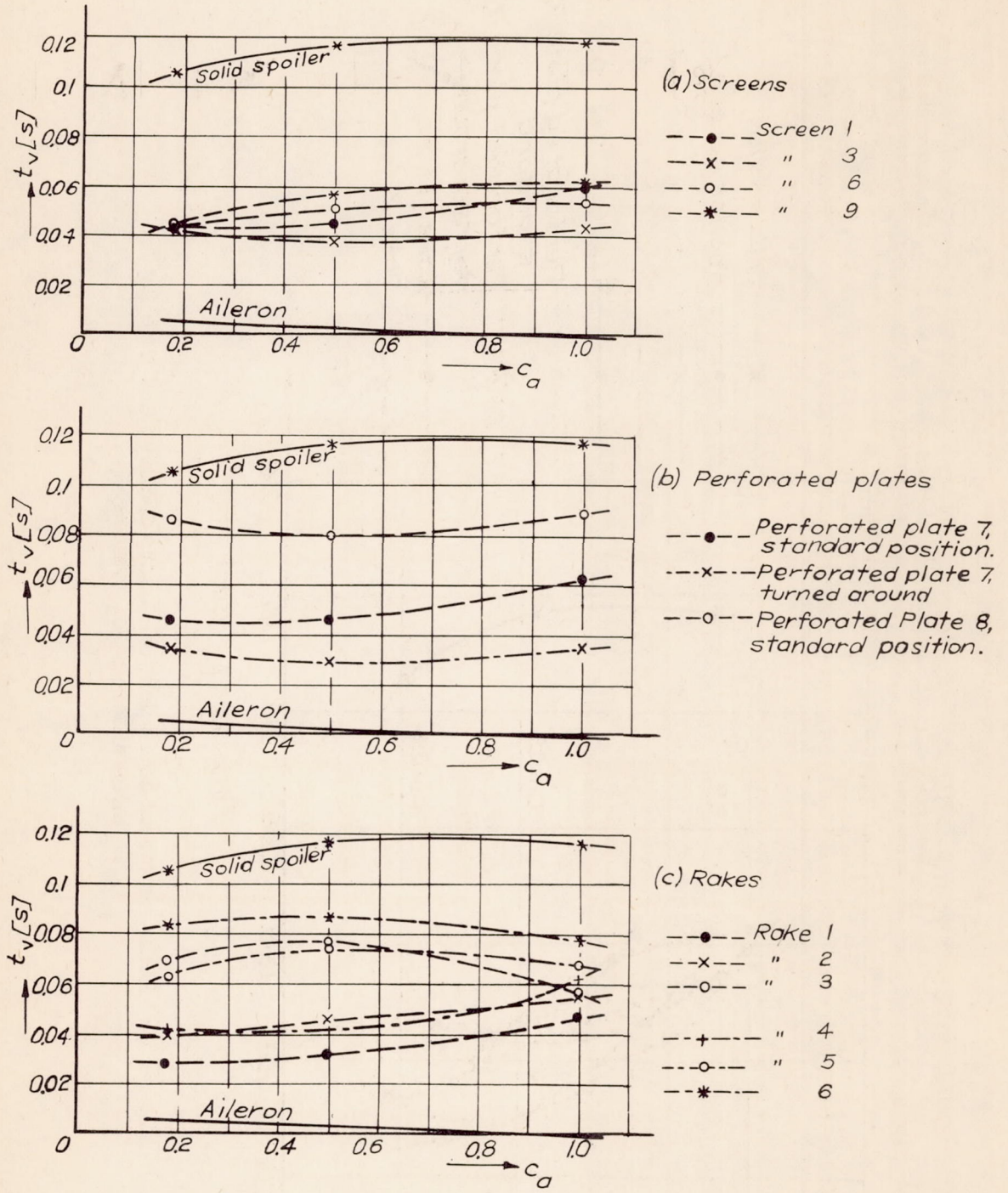


Figure 6.- Measured time lags of various spoilers and of aileron for three different c_a values.

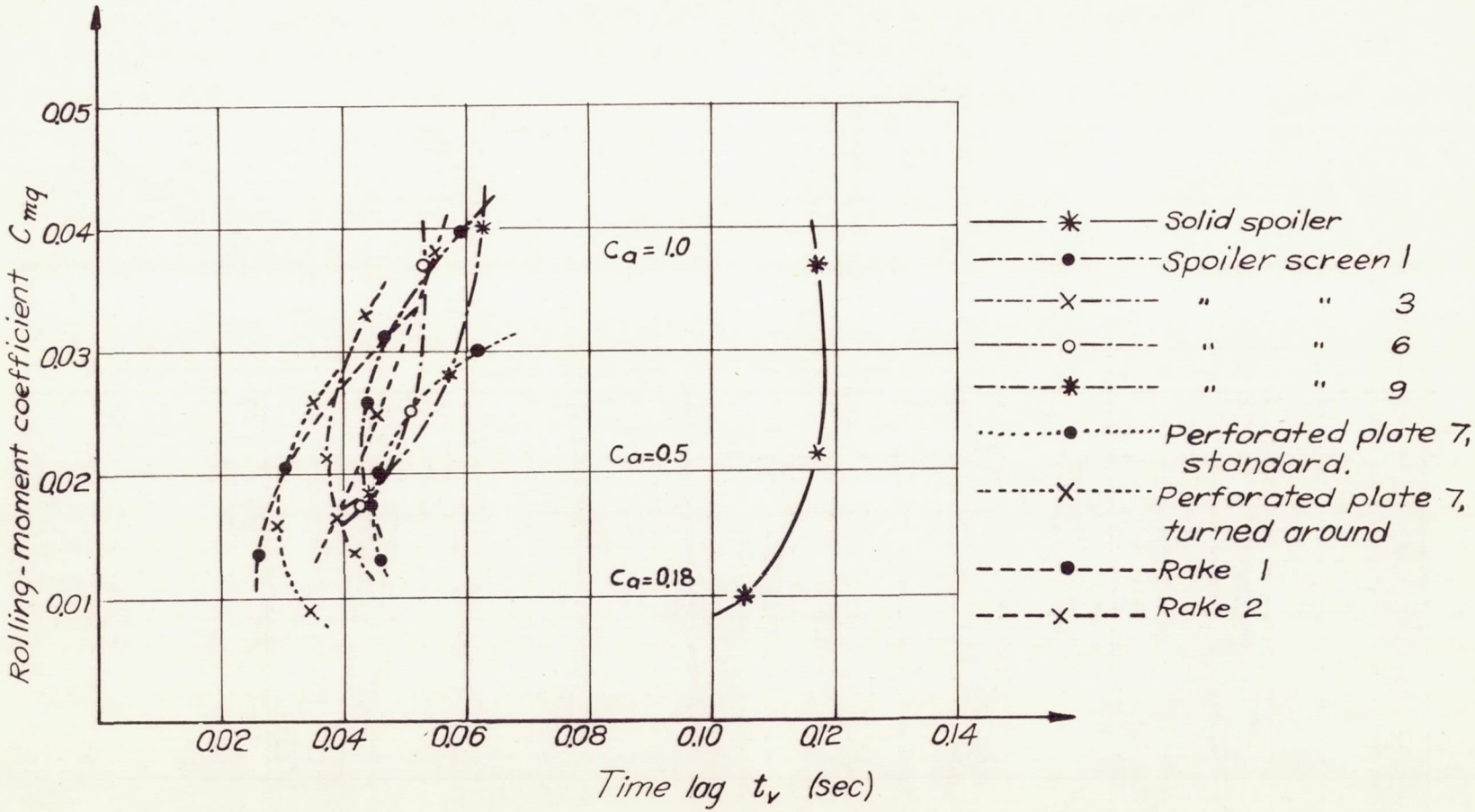


Figure 7.- Rolling-moment coefficient of various spoilers and time lag for three different c_a values.

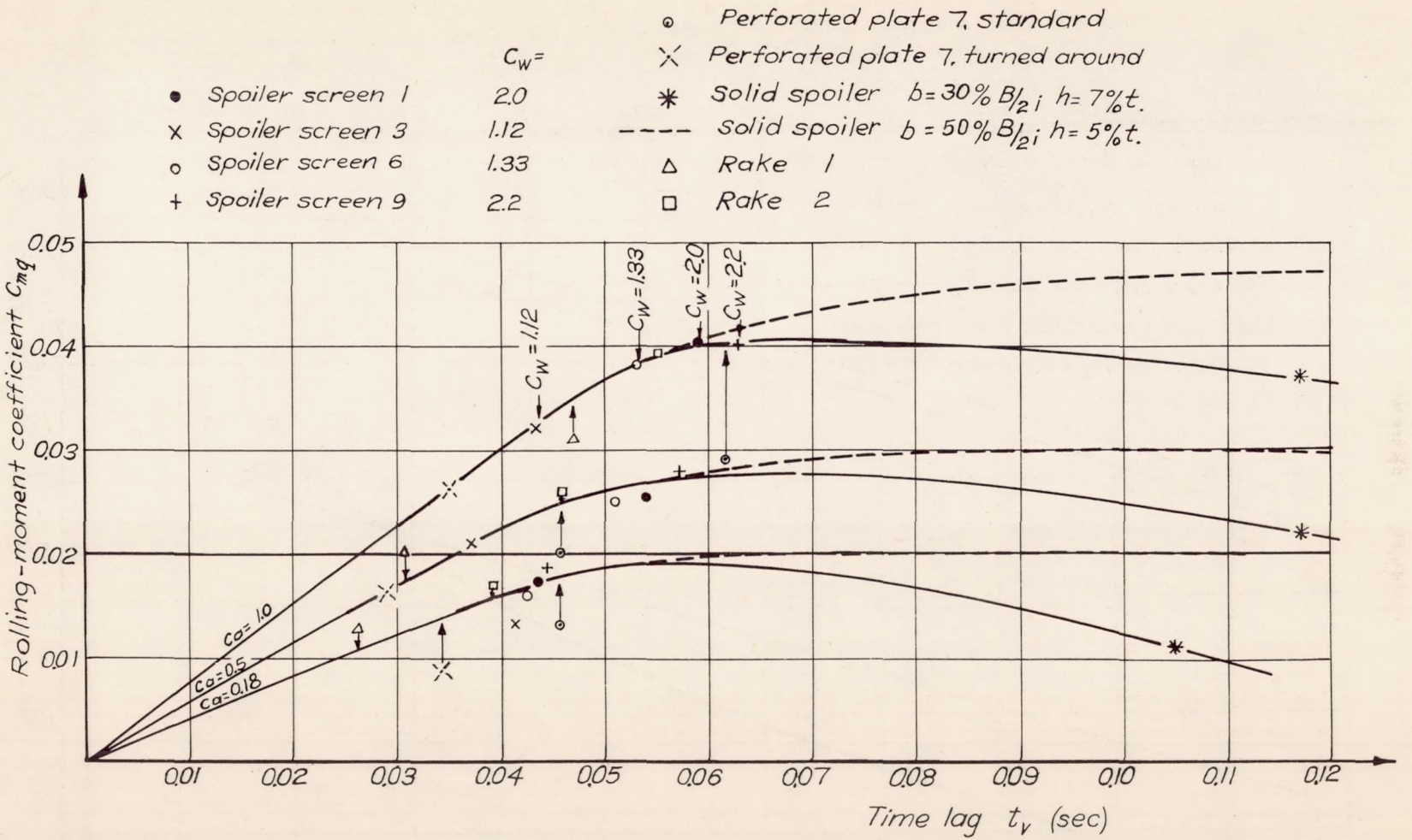


Figure 8.- Relation between time lags and rolling moments for various permeabilities of the spoilers.

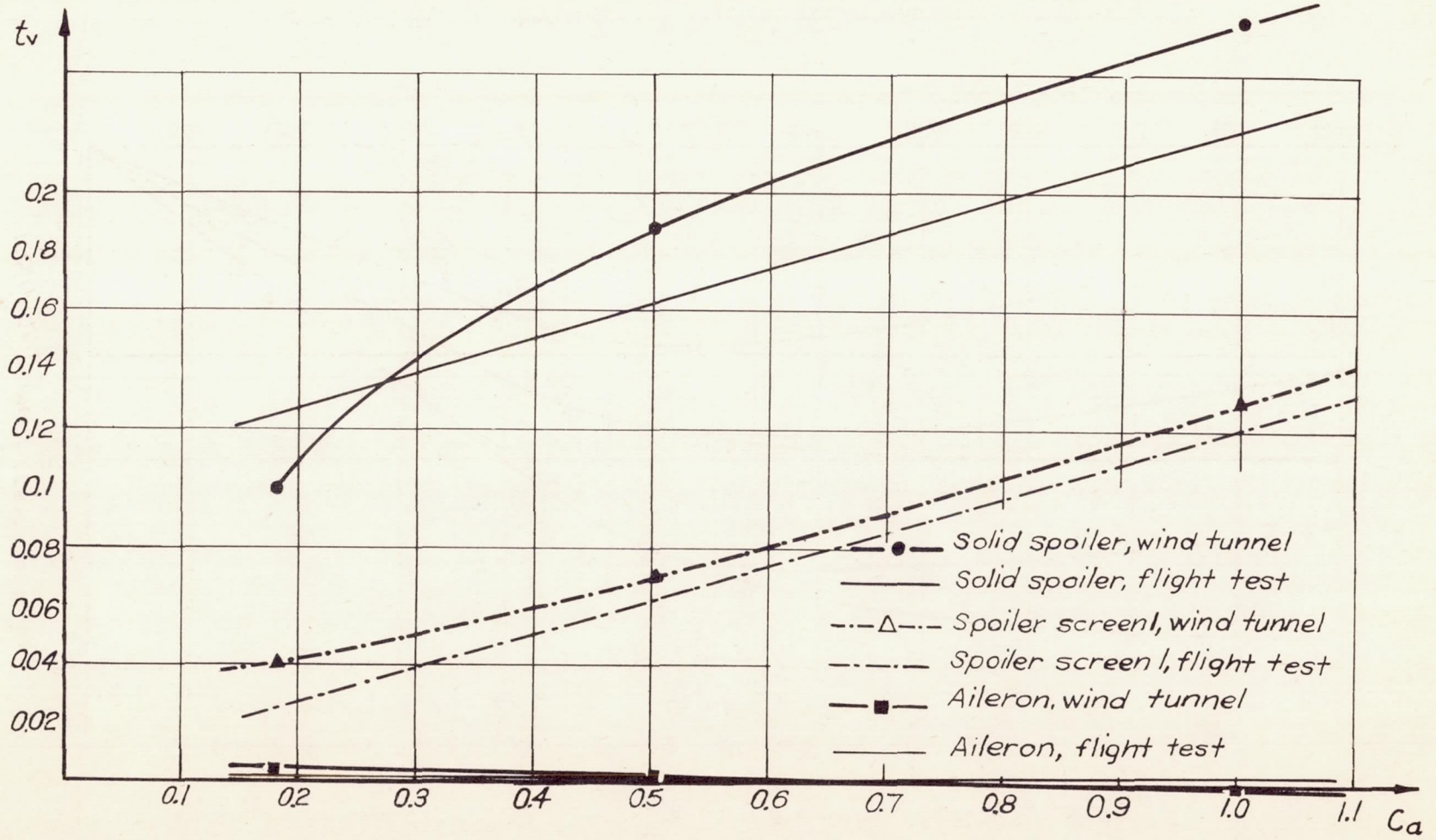


Figure 9.- Comparison between time lags of wind-tunnel tests and those of flight tests (thinly drawn).

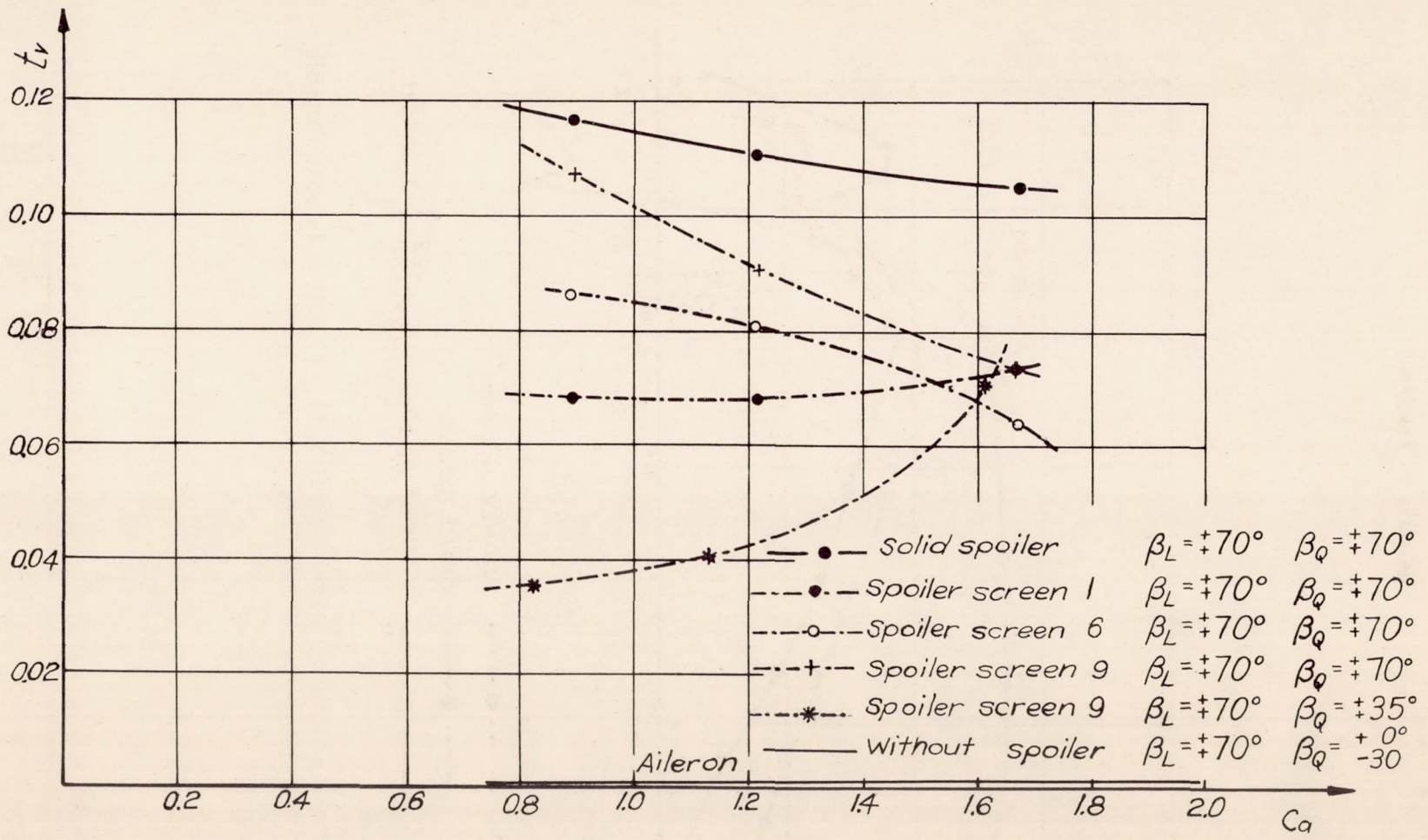


Figure 10.- Time lags of various spoilers and of aileron for deflected landing flaps.

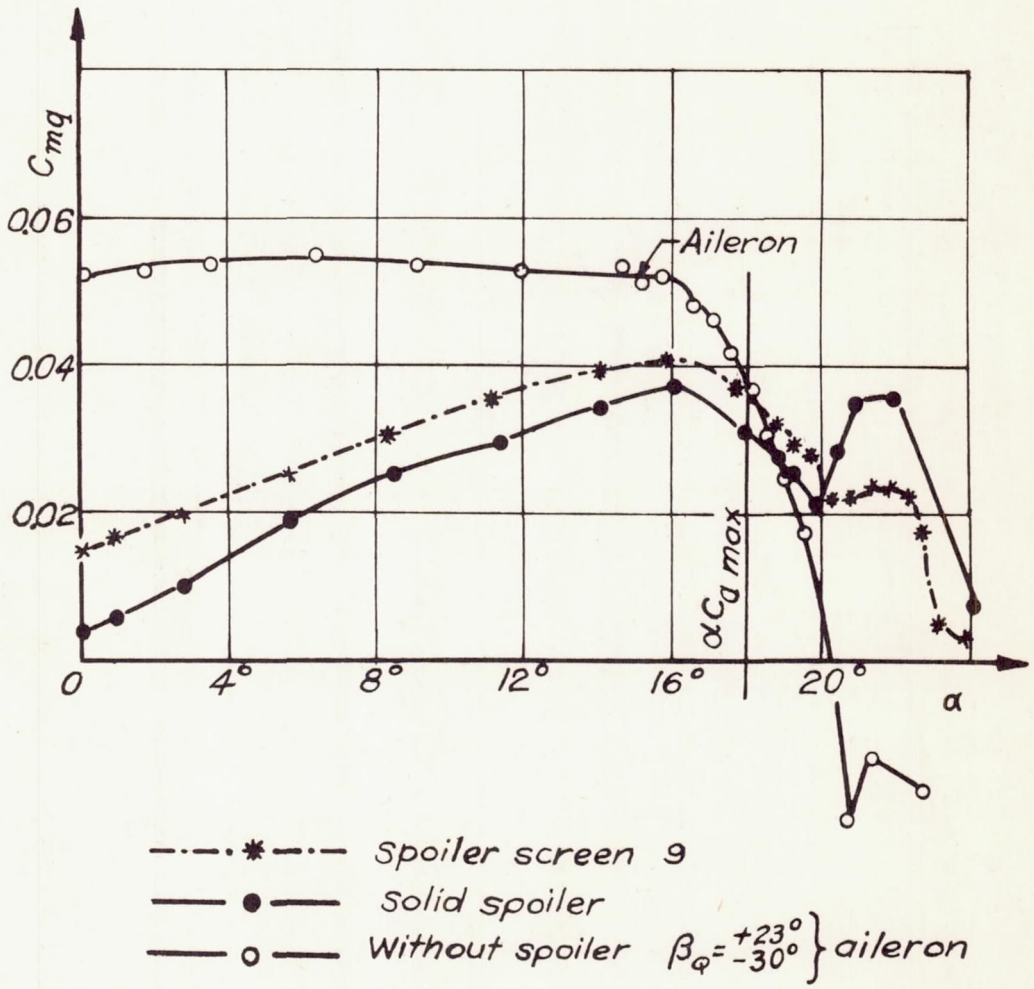


Figure 11.- Rolling-moment coefficient for various lateral controls - $c_{mq} = f(\alpha)$.

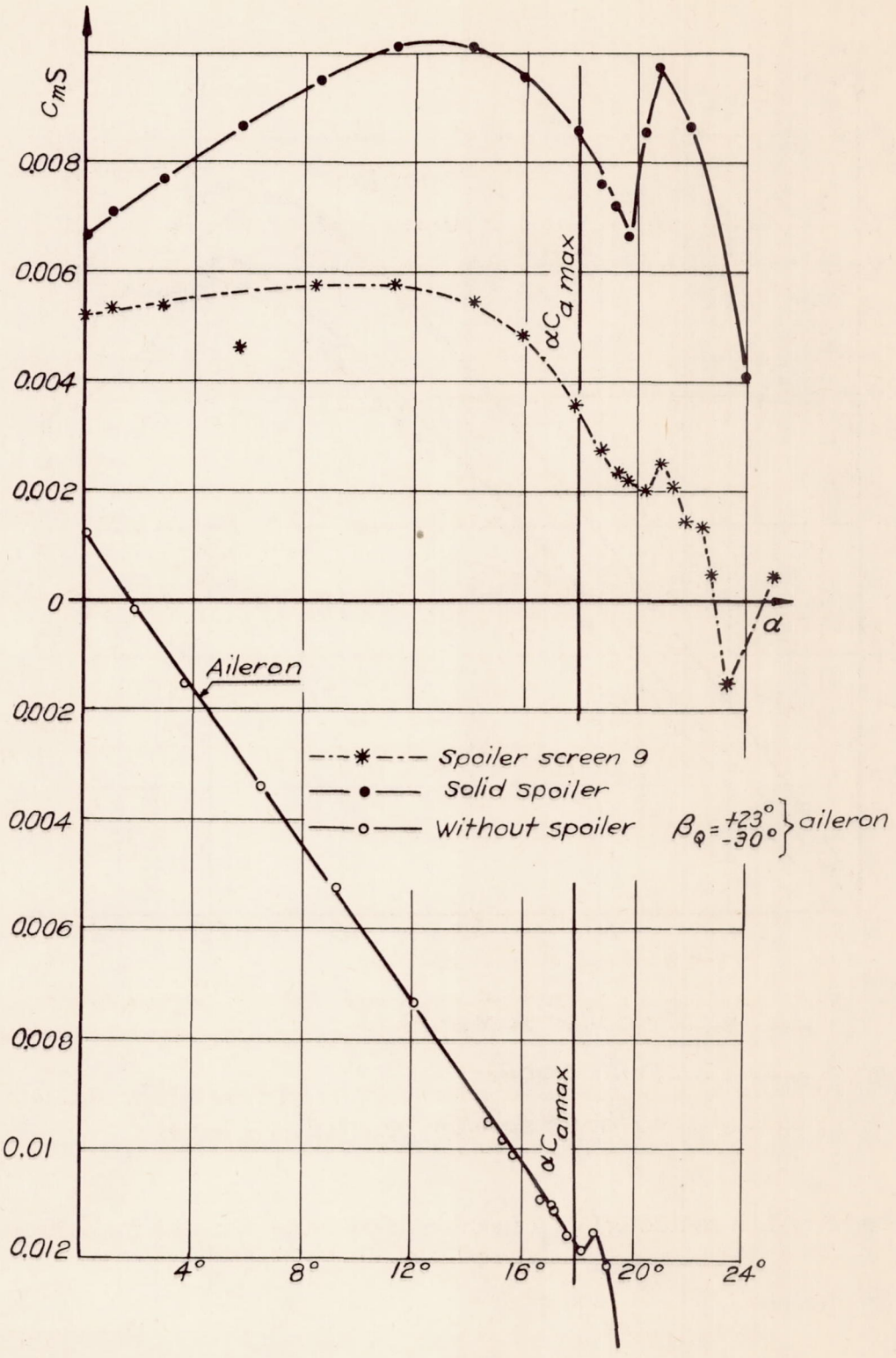


Figure 12.- Yawing-moment coefficient for various lateral controls - $c_{mS} = f(\alpha)$.

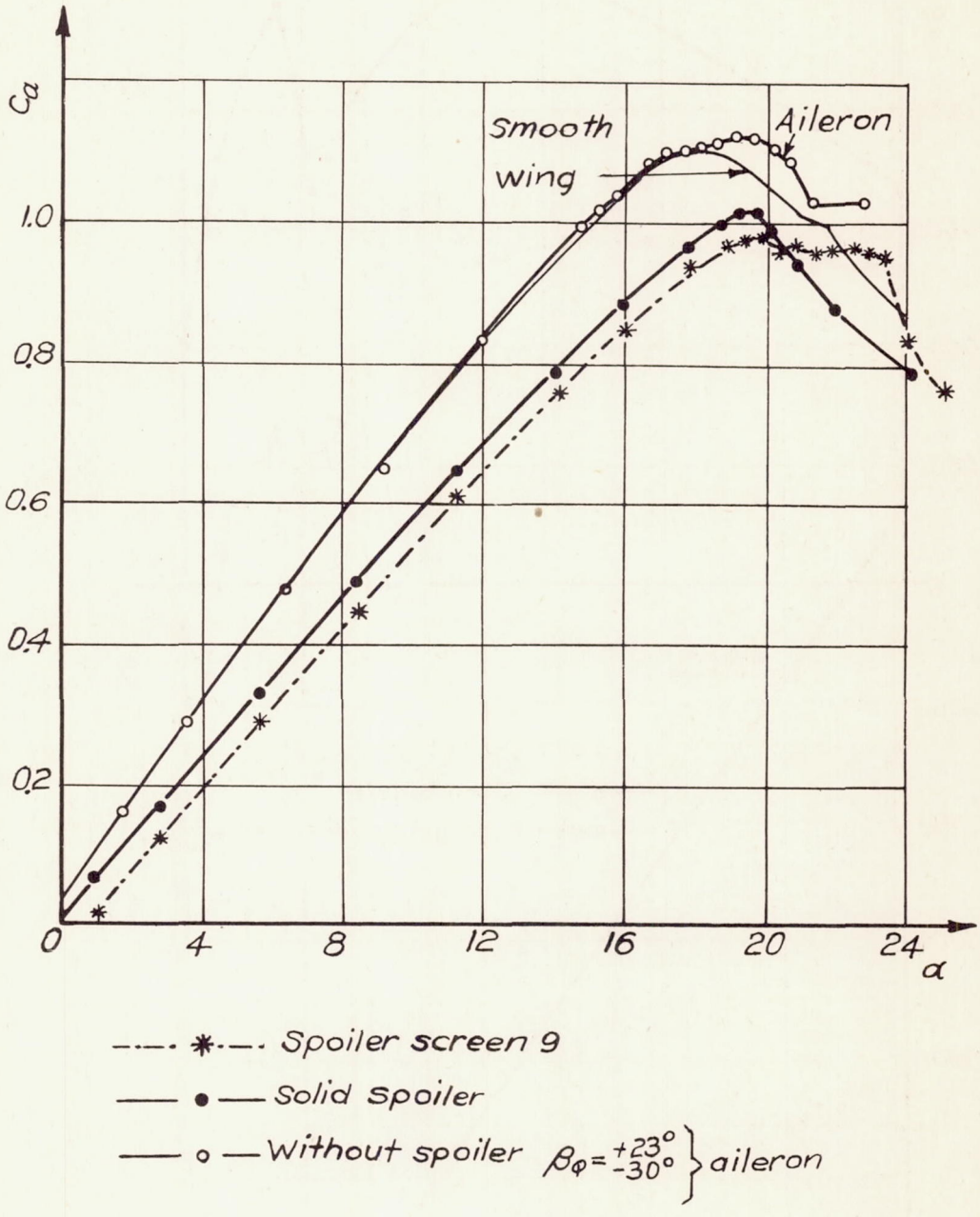


Figure 13.- Lift coefficient as a function of the angle of attack for deflected lateral control.

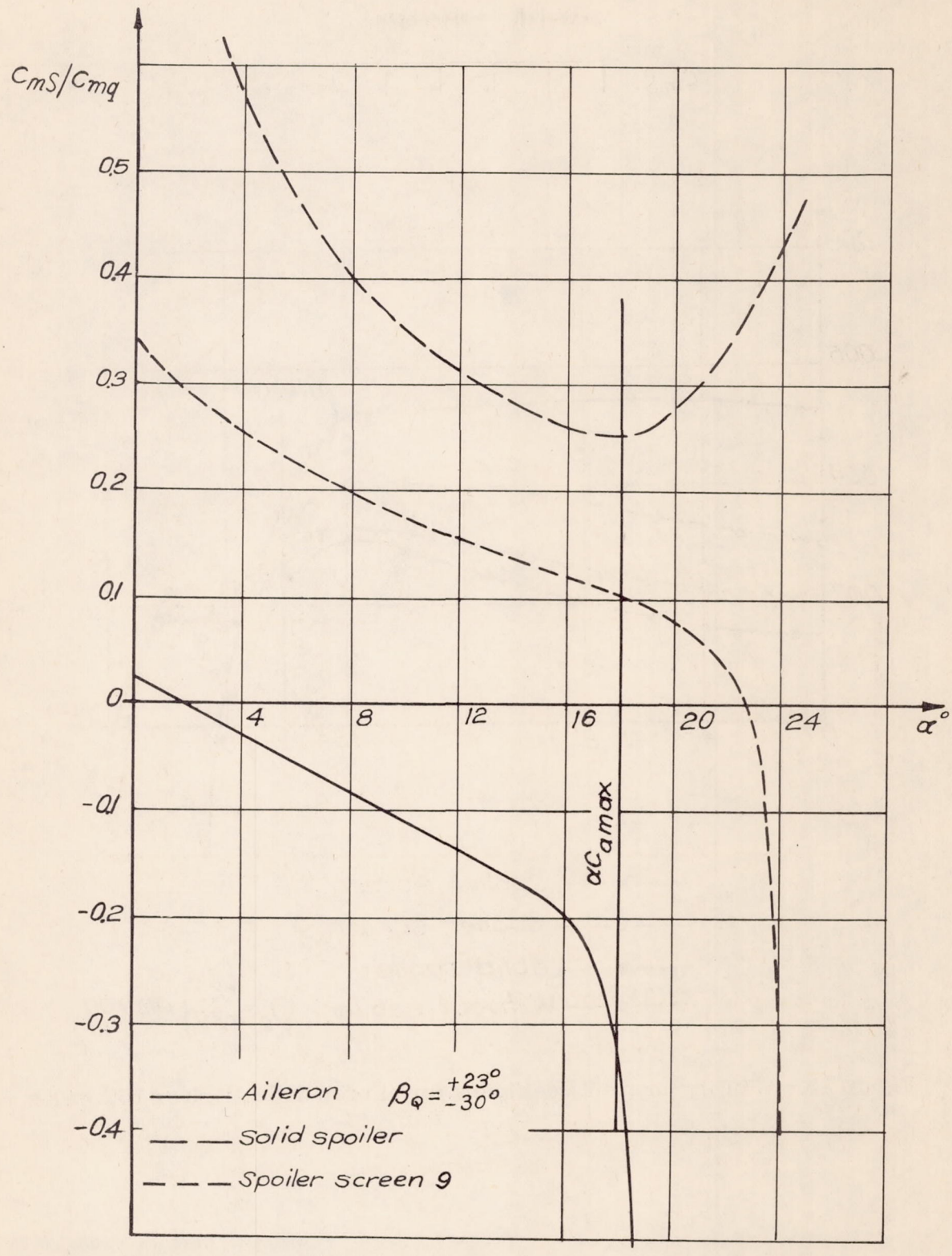


Figure 14.- Ratio of yawing to rolling moment for various lateral controls - $C_{mS}/C_{mq} = f(\alpha)$.

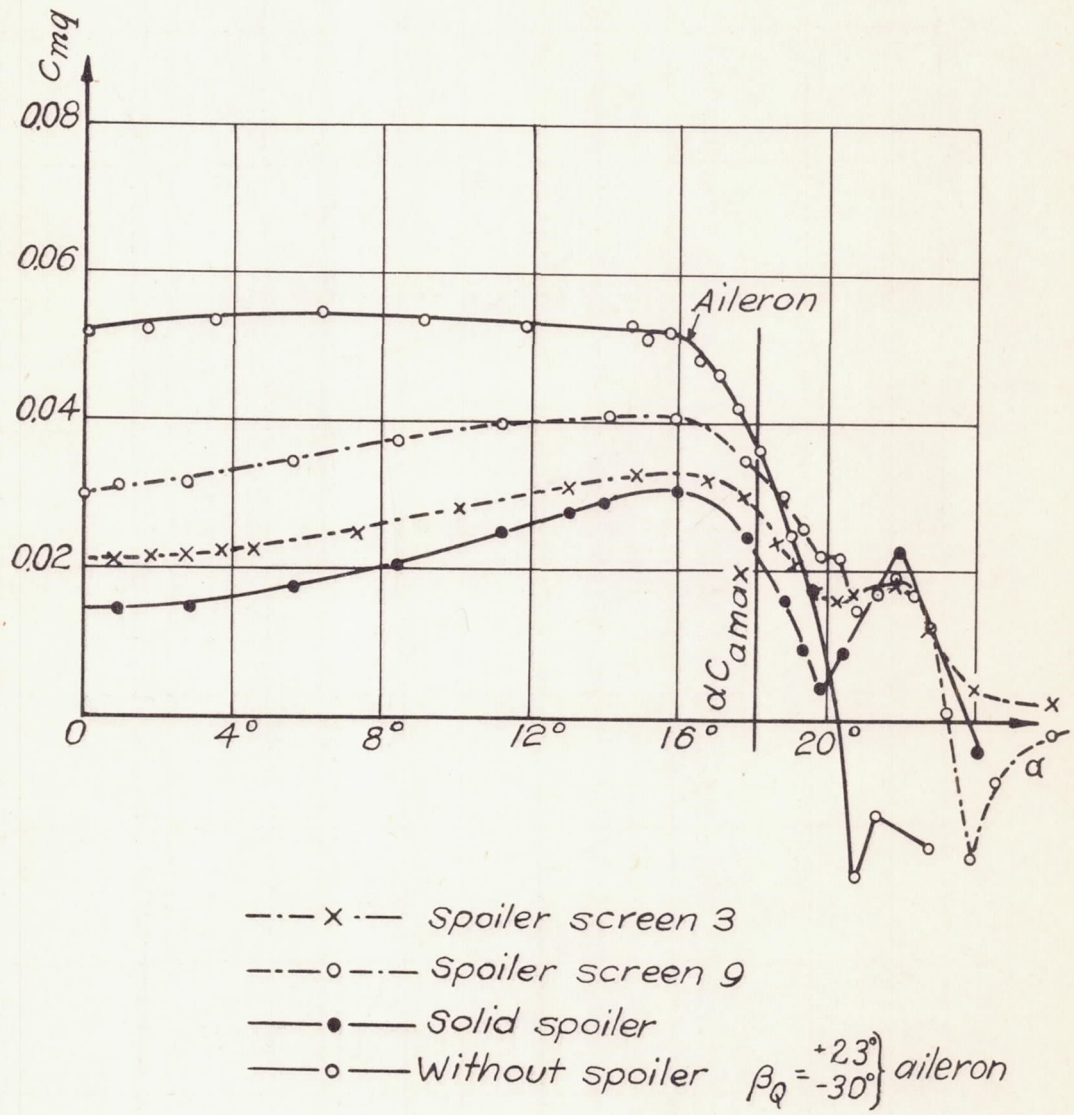


Figure 15.- Rolling-moment coefficient for aileron deflections on both sides - $c_{mq} = f(\alpha)$.

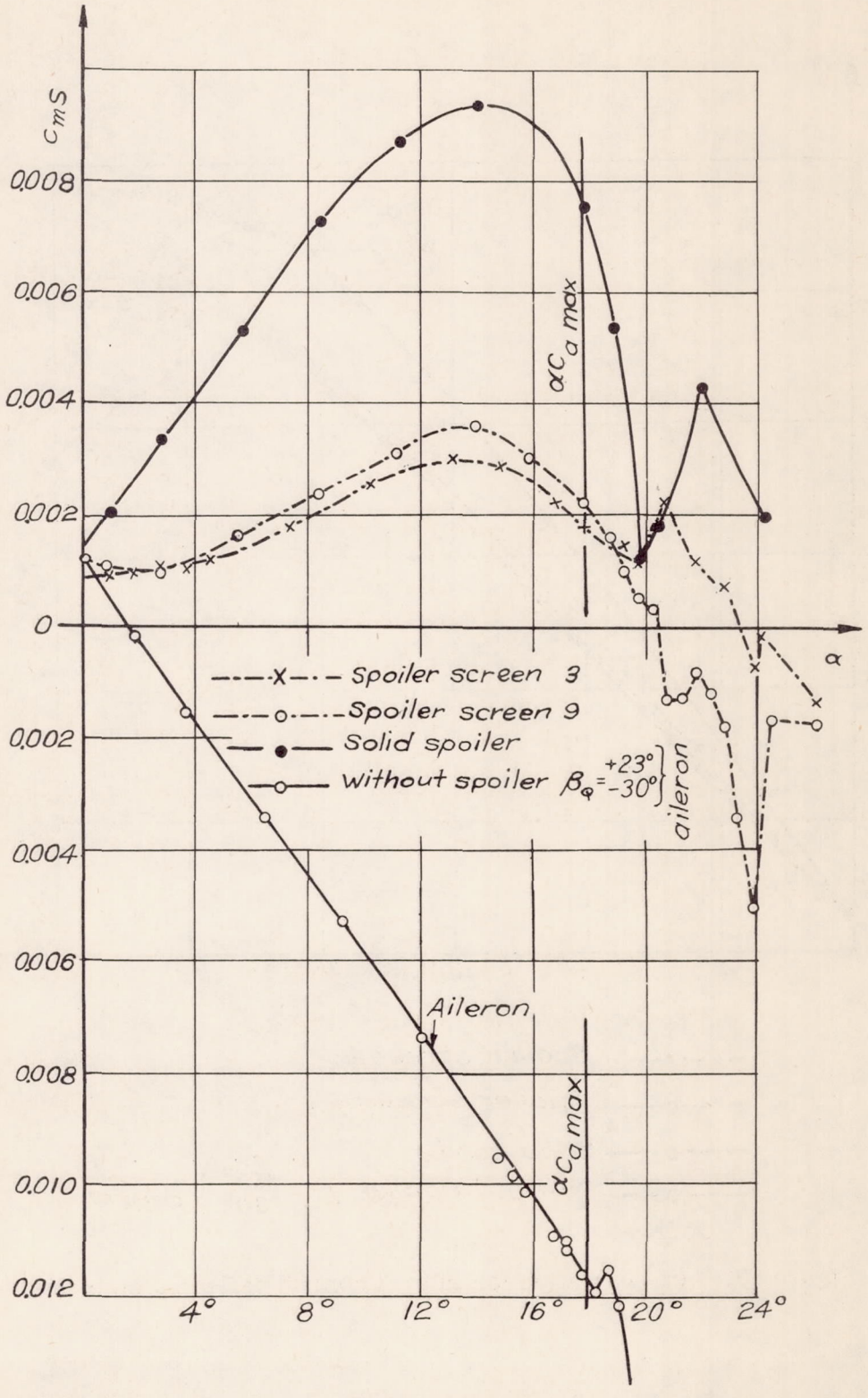


Figure 16.- Yawing-moment coefficient for lateral-control deflections on both sides - $c_{mS} = f(\alpha)$.

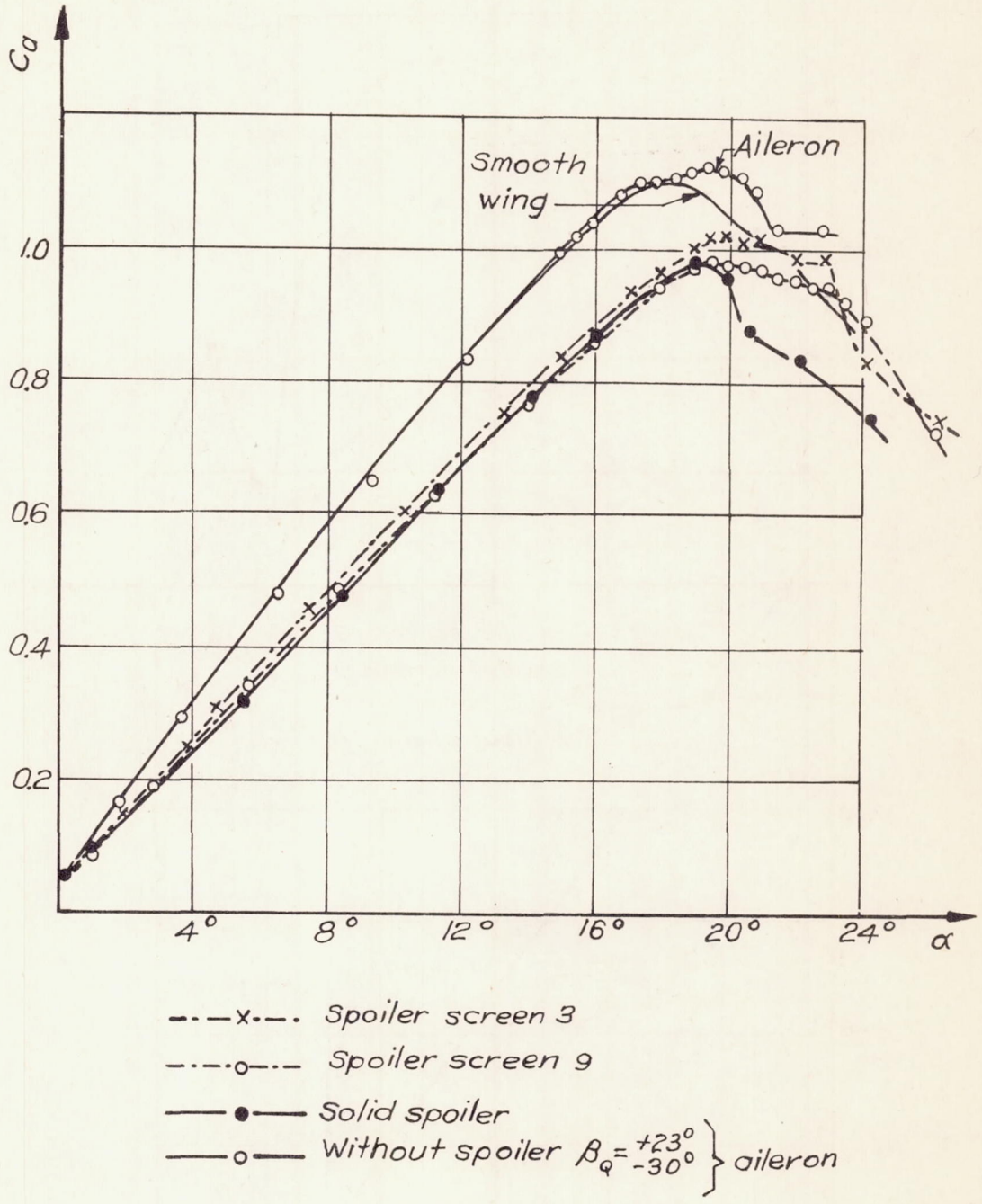


Figure 17.- c_a variation for lateral control deflected on both sides.

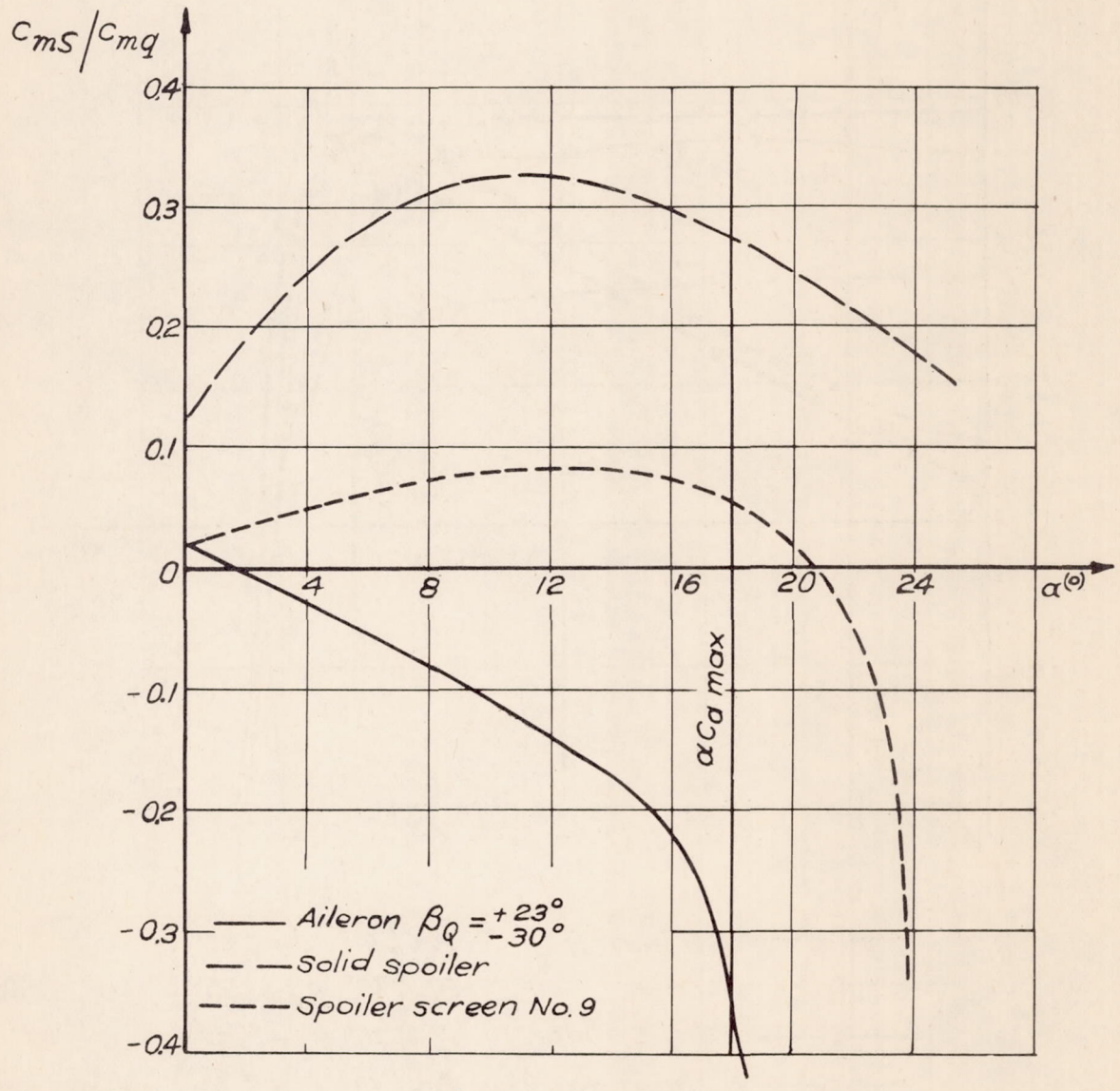


Figure 18.- Ratio of yawing to rolling moment for lateral-control deflections on both sides - $c_{mS}/c_{mq} = f(\alpha)$.

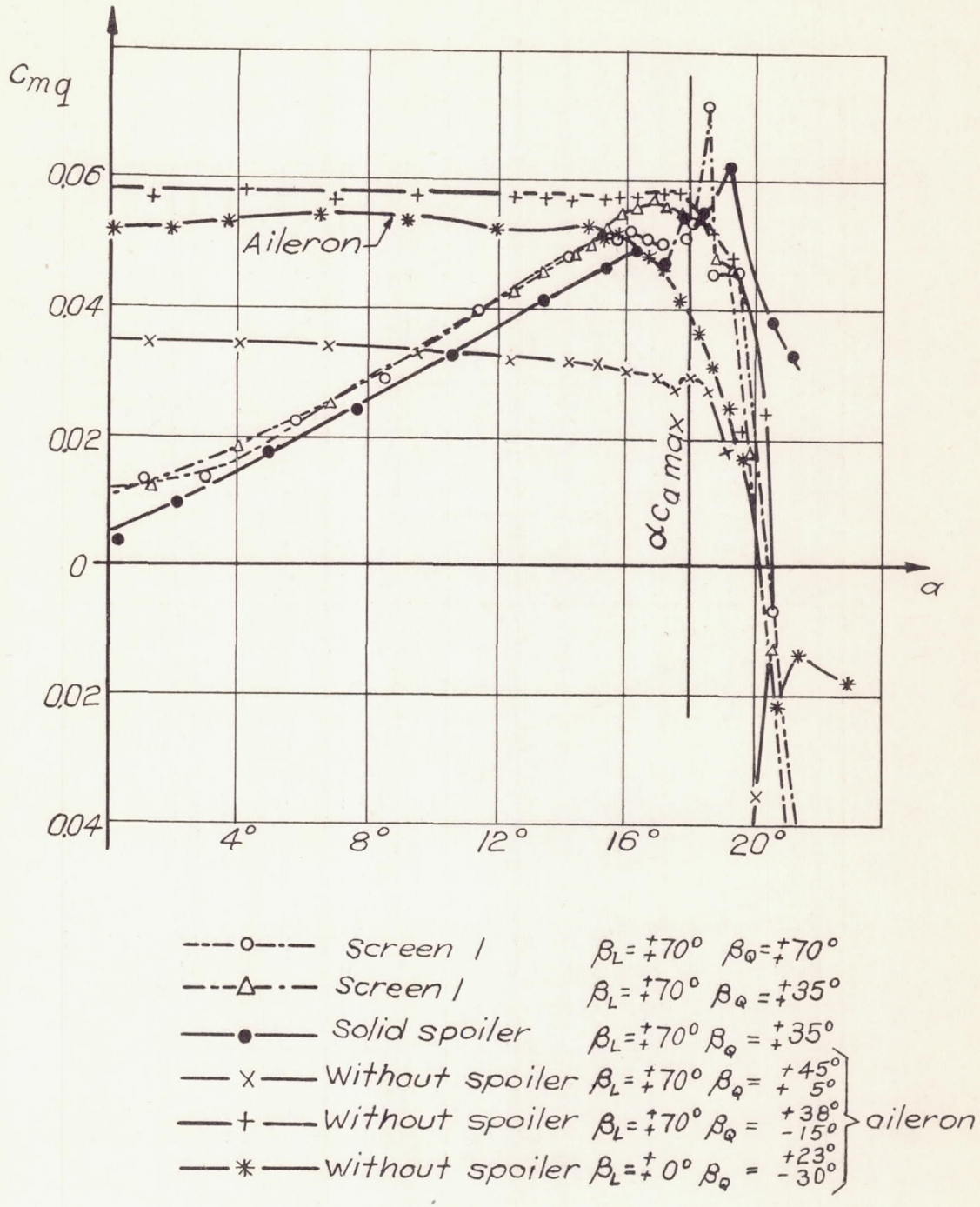


Figure 19.- Rolling-moment coefficient for various lateral controls with landing flaps - $c_{mq} = f(\alpha)$.

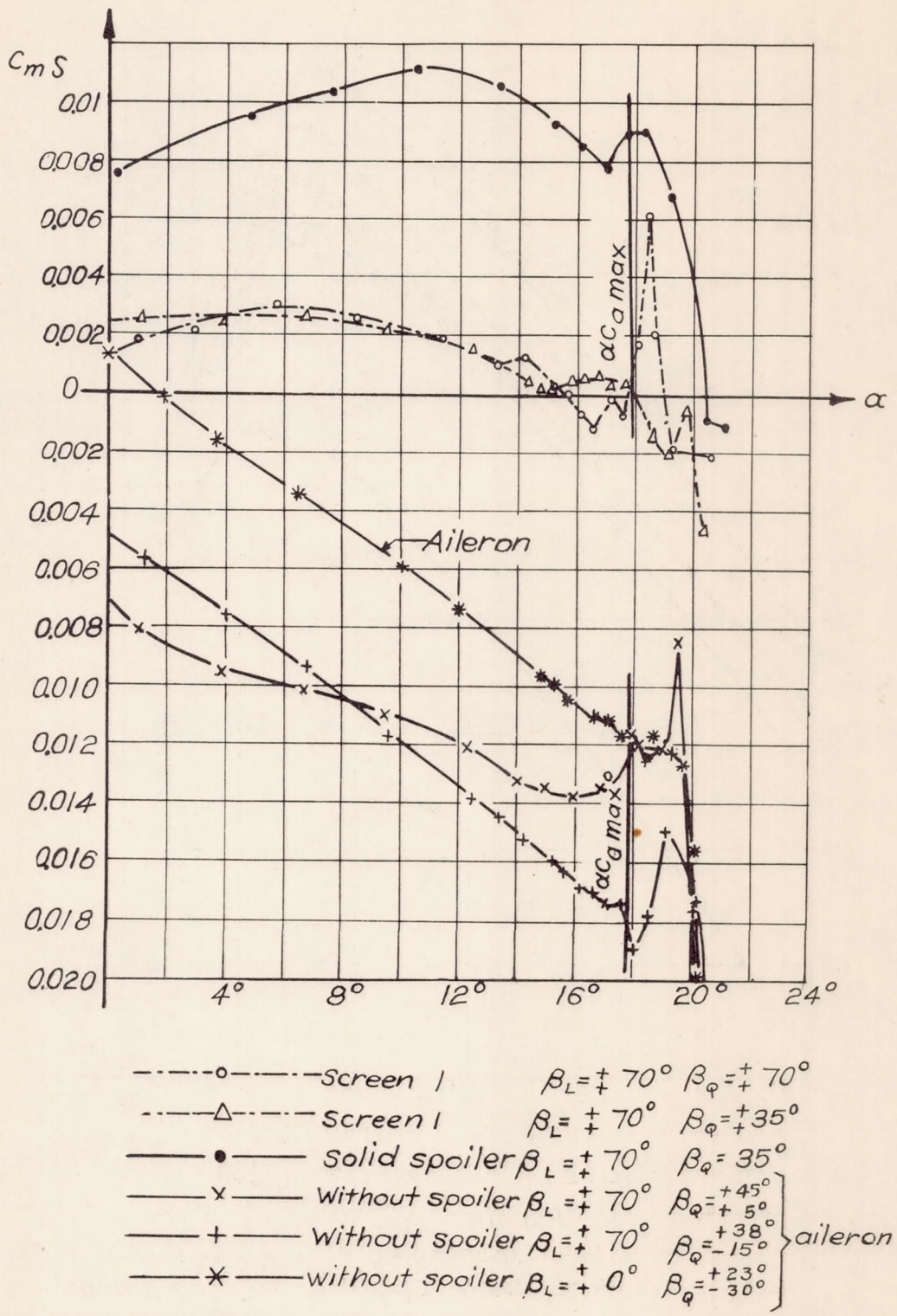


Figure 20.- Yawing-moment coefficient for various lateral controls with landing flaps - $c_{mS} = f(\alpha)$.

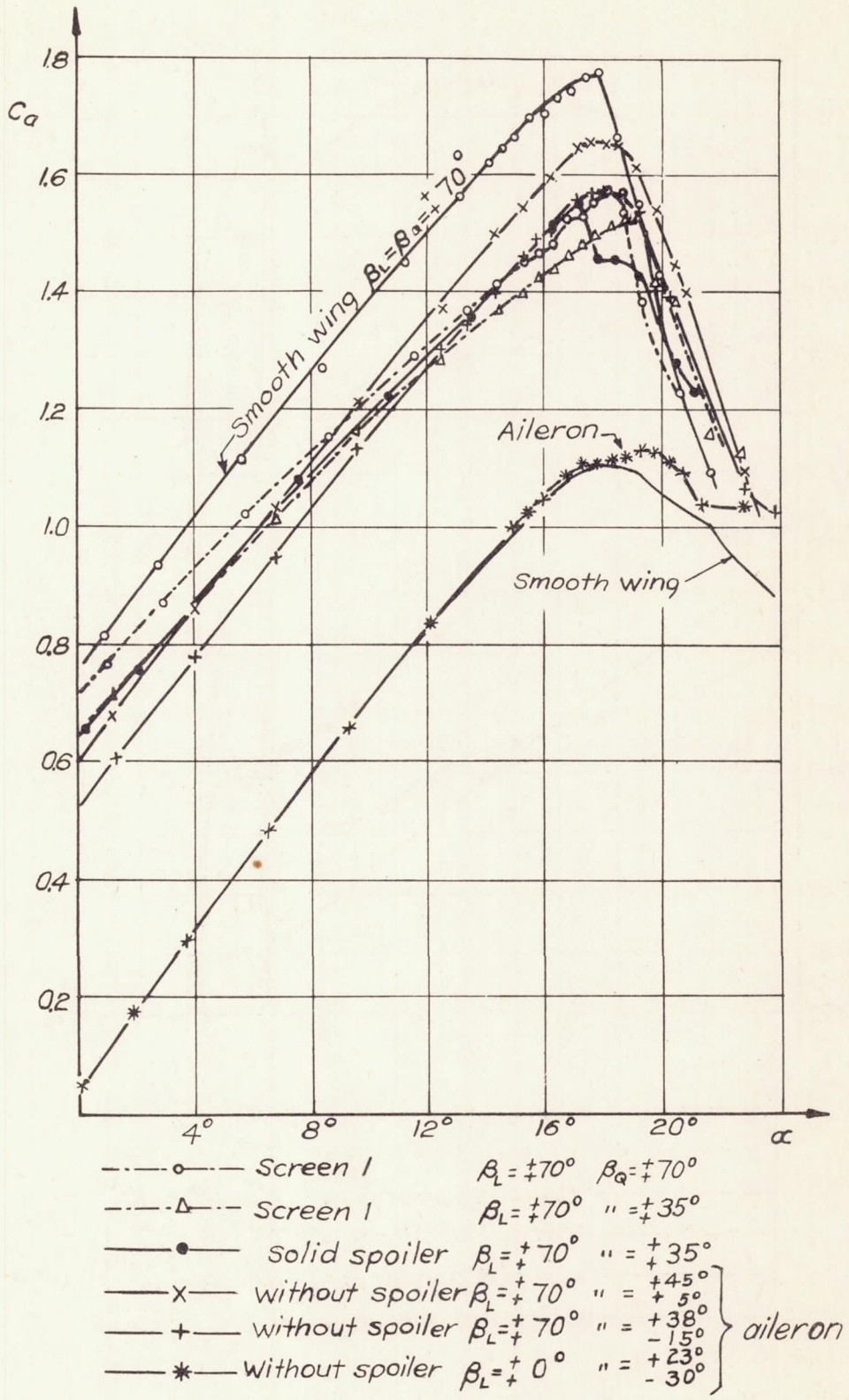


Figure 21.- c_a variation for various lateral controls with landing flaps.

PART II. CONTRIBUTION TO THE LATERAL CONTROL BY SPOILERS AT THE DVL

By M. Kramer

Outline:

I. INTRODUCTION
II. THE YAWING MOTION FOR ABRUPT ACTUATION OF LATERAL CONTROL
III. VARIATION WITH TIME OF THE ROLLING MOMENTS
IV. VARIATION WITH TIME OF THE ROLLING ANGLE
V. SUGGESTION FOR IMPROVEMENT OF THE PERMEABLE SPOILER
VI. THE SPOILER AT HIGH FLIGHT VELOCITIES
VII. SUMMARY
VIII. REFERENCES

I. INTRODUCTION

The wind-tunnel measurements (references 1 and 2) provided data on the static behavior of permeable spoilers. However, a comparison with corresponding flight tests shows that it is not sufficient to make - on the basis of static measurements - statements regarding suitable development of the control for flight requirements. Therefore, the dynamic behavior of the control is calculated below, and hence a conclusion is drawn for further control improvement.

II. THE YAWING MOTION FOR ABRUPT ACTUATION OF LATERAL CONTROL

The exact calculation of the rolling process is difficult because the spoiler produces simultaneously with the desirable rolling moment a large yawing moment so that in case of actuation of the lateral control, a rotation about two axes takes place, with the two axes closely coupled. (Coupling elements are: rolling moment due to yaw, rolling moment due to sideslip, and yawing moment due to roll.) However, introducing numerical values into the calculation, one sees very soon that the calculation may be considerably simplified. The following simplifications are permissible:

1. The main disadvantage in spoiler control, the time lag, exerts its strongest effect at the beginning of the rolling motion. If the different controls are adjusted to provide an equal static rolling moment (and the measurements in the large wind tunnel show this to be possible at least for large c_a-values), the factor $\Delta t/t_Q$ (fig. 1) decreases - for large rolling angles - more and more; this means that the investigation of the lag may be limited to small rolling angles; for large ones, it loses its significance.

2. Since the yawing motion sets in without lag, thus leads the rolling motion, and since only small rolling angles have to be considered, the effect of the rolling on the yawing motion may be neglected (yawing moment due to rolling = 0).

Consideration of the simplifications mentioned leads to first determining the yawing motion, and later taking its effect into account in determining the rolling process. The differential equation of the yawing motion reads

$$A = B\beta'' + C\beta' + D\beta$$

β angle of sideslip

A static yawing moment of the lateral control $c_{m_s} qFb$

B moment of inertia about the vertical axis fixed in the airplane J_z

C damping-in-yaw $A\frac{l_s^2}{v}\left(\frac{dc_q}{d\beta}\right)F_s q$

D directional stability $\frac{dc_{m_s}}{d\beta} qFb$

This simple differential equation may be solved analytically. Since, however, the rolling motion is suitably solved by step-by-step integration because of the discontinuous course of the rolling moments, application of the same method is advisable for the integration of the yawing motion as well.

The representative calculation was carried out on a model of a modern single-seat fighter (Me 109). Figure 2 shows the calculation precedure of the stepwise integration, figure 3 the result, the variation with time of the yawing motion with solid spoiler. The calculation was made first for a large c_a-value ($c_a = 1.2$). The behavior in case of small c_a-values is discussed later.

For want of exact values, the moments of inertia were calculated from a guiding formula; likewise the directional stability was taken as "standard value" from reference 3. The yawing moment of the various lateral controls was estimated on the basis of the measurements in the

large wind tunnel. The calculation is based on the following numerical values:

Wing loading G/F	= 110 kg/m^2
Aerodynamic wing area F	= 16.35 m^2
Lift coefficient c_a	= 1.2
Flight velocity v	= 38.2 m/s
Dynamic pressure q	= 91.5 kg/m^2
Span b	= 9.8 m
Over-all length l	= 8.65 m
Area of vertical tail surfaces F_s	= 1.48 m^2
Distance from vertical tail surfaces to center of gravity l_s	= 5.3 m

Moments of inertia J_x, J_y, J_z

$$J_y = \frac{G}{g}(0.16l)^2 = 342 \quad \text{(standard range 14 to 17 percent } l\text{)}$$

$$J_x = \frac{G}{g}(0.115b)^2 = \underline{228} \quad \text{(standard range 10 to 13 percent } b\text{)}$$

$$J_z = J_x + J_y = 570$$

Yawing-moment coefficients for full deflection of the lateral controls:

c_{m_s} (aileron) = 0.0

c_{m_s} (solid spoiler) = 0.022

c_{m_s} (rake, c_w = 2.0) = 0.017

} $fc_{mq} = 0.04$

Gradient of the vertical tail surfaces

$$dc_q/d\beta = 2.5$$

Directional stability

$$dc_{m_s}/d\beta = 0.057$$

III. VARIATION WITH TIME OF THE ROLLING MOMENTS

The lateral control cannot be actuated infinitely rapidly. In the large wind tunnel, the actuation time was 1/30 second for 0.77 meter mean wing chord at the location of the spoiler and 50 meters per second blower stream velocity (reference 2).

If the discontinuous course of the rolling moments is to be exactly transferable to conditions in flight, one must multiply (taking into account the dynamic characteristics) all times of the tunnel measurement by the factor:

$$\frac{\text{mean wing chord at location of spoiler - full-scale}}{\text{mean wing chord at location of spoiler - model}} \times \frac{\text{flight velocity - model}}{\text{flight velocity - full-scale}}$$

The mean wing chord at the location of the spoiler is 1.67 meters in flight, 0.77 meter on the model, the velocity 38.2 meters per second in flight, 50 meters per second on the model. Thus, the actuation time in flight is

$$t_b = \frac{1}{30}\left(\frac{1.68}{0.77}\frac{50}{38.2}\right) = 2.85 \times 0.33 \cong 0.1 \text{ second}$$

On the basis of flight tests made so far, an actuation time of 1/10 second in flight appears attainable so that the variation with time of the rolling moment of the tunnel measurement may be transferred exactly to flight conditions, the time scale factor 2.85 (fig. 4) being taken into account.

The yawing motion was calculated for abrupt onset of the yawing moment. Actually the yawing moment increases during the actuation time from zero to its maximum value. To take this behavior into account, the yawing moment is assumed to set in suddenly after the lapse of 2/3 of the actuation time (fig. 4).

The rolling moment caused by the yawing motion is divided into two portions, the rolling moment due to yaw and the rolling moment due to sideslip.

Corresponding to reference 4, the coefficient of the rolling moment due to yaw is for elliptic lift distribution and an aspect ratio of 6:

$$c_{mq}(\beta') = \frac{c_a b \beta'}{8v} = \frac{1.2 \times 9.8 \times \beta'}{8 \times 38.2} = 0.038\beta'$$

A standard value of the coefficient of the rolling moment due to sideslip is

$$dc_{mq}/d\beta = 0.057$$

thus, the contribution of the sideslip-angle variation to the rolling moment

$$c_{mq}(\beta) = 0.057\beta$$

Figure 4 shows the rolling moment caused by the yawing motion plotted as a function of time for the solid spoiler. The permeable spoiler causes, due to its smaller yawing moments, somewhat smaller rolling moments. Since the standard lateral control as differential control does not produce a noteworthy yawing moment, the yawing moment does not exert any influence there.

Reference 3 gives as the average value of numerous measurements on modern airplanes for the maximum static rolling moment of the lateral control the value 0.03 to 0.04 (for the coefficients of the Pasadena tunnel and independently of the application purpose). This value is to some extent a function of the coefficient and increases in flight to the amount 0.04 to 0.05. The required value of an ideal lateral control for measurement in the large DVL tunnel is therefore

$$c_{mq\ max} = \frac{M_{max}}{qFb} = 0.04$$

(for approximately elliptic lift distribution). The spoiler measurements in the large DVL tunnel (reference 2) show that in case of suitable dimensioning and large c_a-values, this value may be attained for the solid as well as for the permeable spoiler with $c_w = 2.0$. Therefore this value was chosen as basis of the following comparison. If one denotes as the time lag (t_v) of the rolling moments (according to the report on the measurements in the large DVL tunnel (reference 2)) the time from the end of the actuation time to the attainment of the full static rolling moment, there results, with consideration of the time-scale factor 2.85 and extrapolation to $c_a = 1.2$ (fig. 9)

Aileron $t_v = 0$

Solid spoiler = 0.336

Rake ($c_w = 2.0$) = 0.172

The discontinuous measurements show furthermore that with aileron the increase of the rolling moment sets in at the beginning of the actuation time with solid spoiler and with rake at the end of the actuation time. Everything that was said before was summarized and the variation with time of the rolling moments for the different lateral controls was accordingly plotted in figure 4.

IV. VARIATION WITH TIME OF THE ROLLING ANGLE

With φ denoting the rolling angle, the differential equation of the rolling motion reads

$$E = F\varphi'' + G\varphi'$$

In this equation

E = the instantaneous value of the rolling moment = $c_{mq} \cdot qFb$ (c_{mq} from figure 4).

F = the moment of inertia about the x-axis, the estimation of which was discussed in the previous section.

G = moment of damping-in-roll = $c_{mq}(\varphi')qFb$

The coefficient of damping-in-roll is according to reference 4 for elliptic lift distribution and an aspect ratio of 6:

$$c_{mq}(\varphi') = \frac{1}{16} \frac{dc_a}{d\alpha} \frac{b}{v}$$

It must be noted that the spoilers reduce the value $dc_a/d\alpha$. The only useful information regarding this reduction in damping may be taken from reference 1. Hence it follows that the solid and the permeable spoiler reduce $dc_a/d\alpha$ of the two-dimensional problem for the values used also in the large tunnel (5 percent height of spoiler and 20 percent rearward position of spoiler) by about 42 percent. If the spoiler is deflected only on one wing half and extends very far inward on this wing half (from 90 percent b/2 to 40 percent b/2), the assumption that the damping-in-roll is reduced by 20 percent by spoiler application appears justified.

The differential equation of the rolling motion was again solved by stepwise integration. Figure 5 shows as an example the calculation procedure for the standard aileron. The result of the calculation, the variation with time of the rolling angle for the three lateral controls (standard aileron, solid spoiler, and permeable spoiler (rake $c_w = 2.0$)) is represented in figure 6. Besides those named in the previous section, the following numerical values form the basis of the calcualtion:

$dc_a/d\alpha$ (standard aileron control) = 4.0

$dc_a/d\alpha$ (spoiler) = 3.2 (20 percent reduction in damping)

V. SUGGESTION FOR IMPROVEMENT OF THE PERMEABLE SPOILER

The measurements in the large wind tunnel have shown that it is possible to considerably reduce the time lag t_v of the solid spoiler by the introduction of the permeable spoiler; then it becomes difficult, however, to attain the necessary static rolling moment below a permeability which corresponds to a c_w-value of about 2.0 for insertion of the spoilers into a pipe line. A $c_w \cong 2.0$ therefore forms the limit for the simple principle of permeability. If the permeability is further increased, the rolling motion will start earlier; however, since the moments are smaller than those of standard lateral control, a lag now occurs on the basis of insufficient effectiveness. Thus, $c_w = 2.0$ represents an optimum for the permeable spoiler and figure 6 shows that the gain, compared to the solid spoiler, is not very large. Particularly at the start of the motion, the permeability has only little effect; thus, it is understandable that the flight tests where the start of the rolling motion is used as criterion for the improvement show only slight superiority of the permeable over the solid spoiler.

On the other hand, the calculation shows immediately in what direction a further improvement of present results may be expected. It is absolutely necessary that at least part of the rolling moments set in a great deal earlier. This is attainable by using a lead spoiler of high permeability (thus still further reduced aerodynamic lag) and high control speed (thus reduced mechanical lag). For instance, in the further course of the control-stick motion, intermediate teeth can enter into the interspaces of the very suddenly projected rake with relatively wide tooth intervals, so that at the end of the actuation again the rake with $c_w = 2.0$ is deflected while previously during a certain period of time a rake of a very much lower c_w-value had been fully deflected.

Figure 7 shows the course of the moments as it is to be expected for such an arrangement. It had been assumed that the spoiler, having low solidity, is deflected in 1/3 of the actuation time,[1] thus up to about 1/3 of the path of the stick (which presupposes a very light structure of the lead spoiler) and that it possesses a c_w of 0.66. For this c_w an insignificant extrapolation of the results of the large DVL tunnel (reference 2) results in a halving of the time lag compared to the rake

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[1]The assumption 1/3 actuation time is extreme. In view of the mass forces and of the static course of the rolling moment as a function of the stick path, it will probably be possible only to realize a factor of 1/2.

with $c_w = 2.0$ and in a reduction of the maximum rolling-moment coefficient to 55 percent. The course of the moments according to figure 7 was used, in the manner described before, for the determination of the course of the rolling motion.

Figure 8 represents a comparison of the "permeable spoiler with a lead spoiler" (as the lateral control according to figure 7 is called below) with the other lateral controls. A representation which shows more clearly the significance of the lag was selected. Corresponding to figure 1, the ratio $\Delta t/t_Q$ was plotted over the rolling angle so that one can see directly from the diagram the percentile influence of the lag compared to the time required with the standard control. (This representation offers an unequivocal judgment regarding the lag only when, as in the present case, the static rolling moments of the various controls are mutually equalized.)

Figure 8 shows that - in contrast to the permeable spoiler - the permeable spoiler with a lead spoiler promises an essential improvement precisely for small rolling angles, thus for the condition where a lag is felt most strongly. According to the calculation, the permeable spoiler with a lead spoiler reduces the lag (Δt) in the entire calculated range of rolling angles ($1/5^\circ$ to 6°) to about 40 percent of the corresponding value in case of a solid spoiler.

VI. THE SPOILER AT HIGH FLIGHT VELOCITIES

The calculation was carried out only for a relatively high c_a-value, thus, low flight velocity. This is justified by the basic behavior of the time lag t_v (time from the end of actuation to the attainment of the maximum static rolling moment). In figure 9, an evaluation of the tests in the large DVL tunnel shows that fundamentally the time lag t_v decreases with c_a even for constant velocity, percentually the more so, the higher the degree of permeability of the spoiler. Furthermore, one must consider that, for reasons concerning the coefficient, the time lag decreases with the reciprocal value of the velocity, thus approximately with c_a. That is, the lag decreases with c_a so strongly since in high-speed flight no difficulties whatsoever can arise regarding time lag.

The flight results seem to contradict this conclusion, since, according to these tests, the time lag showed a very much lower degree of dependence on the flight velocity. This seeming contradiction is explained by the fact that in flight tests usually the start of rolling motion is used as criterion for the lag, but that this criterion does not unequivocally comprise the time lag t_v; it is also a function of the

absolute magnitude of the rolling moments. Since the spoilers cause a rolling-moment coefficient decreasing with c_a, the reduction in effectiveness must mask the reduction in time lag t_v for the criterion as it is usually used in flight tests, and must lead to the conclusion that the difficulty regarding time lag would exist even in high-speed flight.

Actually, however, the time lag t_v in high-speed flight is only a fraction of the time lag in low-speed flight. Thus, one has to deal in high-speed flight not so much with the time lag as with the problem of how to obtain sufficient effectiveness. In this respect, the counter spoiler, which projects on the pressure side of the wing, signifies an essential improvement since it about doubles the effect in high-speed flight. However, it is still doubtful whether it is desirable that the spoiler effect simulate that of standard lateral control in high-speed flight. Men qualified to judge that question (for instance, Dr. Kupper) were of the opinion that the standard lateral control, when satisfactory in low-speed flight, is over-dimensioned for high-speed flight. Thus, the fact that the spoiler is of reduced effectiveness in high-speed flight might perhaps even mean an advantage. Therefore one should avoid using a lag criterion which mixes up time lag and effect and thus brands as a disadvantage a quality which might turn out to be an advantage.

A possibility which appears usable in flight tests consists in first adjusting the effects - thus the maximum rolling velocity - of the controls to one another, and only then measuring the lags. Under this presupposition the valuation of the time lag from the rolling-angle variation is unequivocal. If the flight tests are carried out on this basis, it will be shown that the time lag in high-speed flight loses its significance and that it is, therefore, of foremost importance to perform comparative flight tests in low-speed flight.

VII. SUMMARY

Earlier measurements (reference 2) have shown that by the use of a spoiler permeable to air, for instance, in the shape of a rake, and arrangement of a corresponding counter spoiler on the pressure side of the wing, the essential defects of spoiler control (as it is known so far) may be alleviated. Rolling moment and yawing moment, in particular, were successfully adapted to practical requirements.

The present report shows that the reduction in time lag obtained by permeability is, in practice, not yet satisfactory and proves that application of an extremely permeable, very rapidly actuated "lead spoiler" promises a further reduction in time lag.

The permeable spoiler with lead spoiler also still shows a time lag, compared to the aileron; this time lag is no longer more than about 40 percent of that of the simple spoiler tested in America; but at the start of the rolling motion (rolling angle 0.5°) - thus precisely at the moment where it is preceived as disturbing to the "feel" - it still amounts to 50 percent of the corresponding rolling time of the aileron.

Whether or not this time lag is now admissible in practice can be decided only by testing in flight. It must be noted that all judgments regarding the lag based on "feel" which are obtained from airplanes of small wing loading are falsified, for the time lag decreases with increasing wing loading and necessarily drops, for large wing loading, below the perception threshold of stimulation. The spoiler control, however, is meant precisely for airplanes of large wing loading. For 150 kilograms per meter^2 the calculation yields, at $c_a = 1.2$ and a comparative rolling angle of 0.5°, a time lag of only about 4/100 second. It is doubtful whether such slight differences in time are still perceived and how far adaptation of the pilot makes them more acceptable if the control is satisfactory with respect to its other properties.

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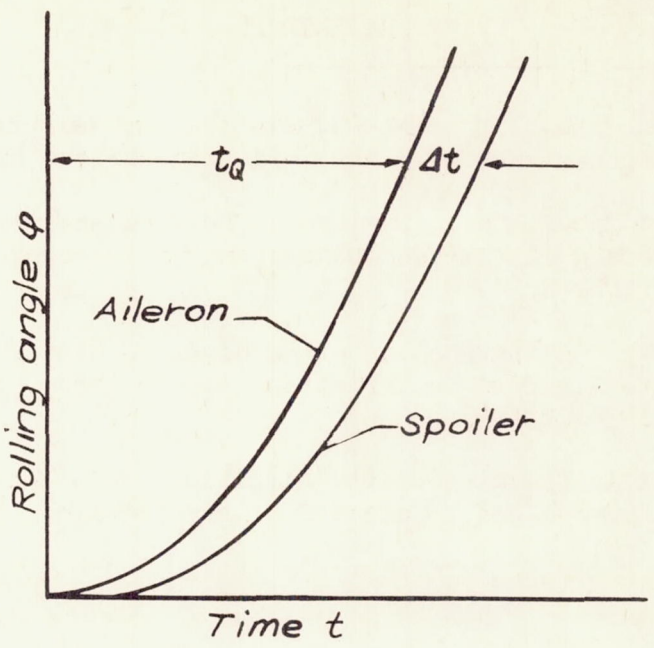

Figure 1.- Representation illustrating the factor t/t_Q.

$$l = 1.77\,\beta'' + 1.01\,\beta' + 2.6\,\beta$$

$$\Delta t = 0.1\ (s)$$

t	β''	$\Delta\beta'$	β'	$\Delta\beta$	β	β^o	Control
0	0.565	0	0	0	0		
.1	.535	.055	.055	.0027	.0037	0.155	0.945 + 0.055 + 0.007 = 1.007
.2	.495	.0515	.106	.0081	.0108	.62	.875 + .107 + .028 = 1.01
.3	.445	.0470	.153	.0130	.0238	1.36	.787 + .154 + .062 = 1.003
.4	.395	.0420	.195	.0175	.0413	2.36	.700 + .195 + .107 = 1.002
.5	.345	.0370	.232	.0214	.0627	3.60	.610 + .232 + .163 = 1.005

$$\Delta\beta' = \frac{\beta''_n + \beta''_{(n-1)}}{2}\Delta t;\quad \beta' = \Delta\beta'_n + \beta'_{(n-1)};\quad \Delta\beta = \frac{\beta'_n + \beta'_{(n-1)}}{2}\Delta t;$$

$$\beta = \Delta\beta_n + \beta_{(n-1)}$$

Figure 2.- Sample of the stepwise integration of the equation of the yawing motion (solid spoiler).

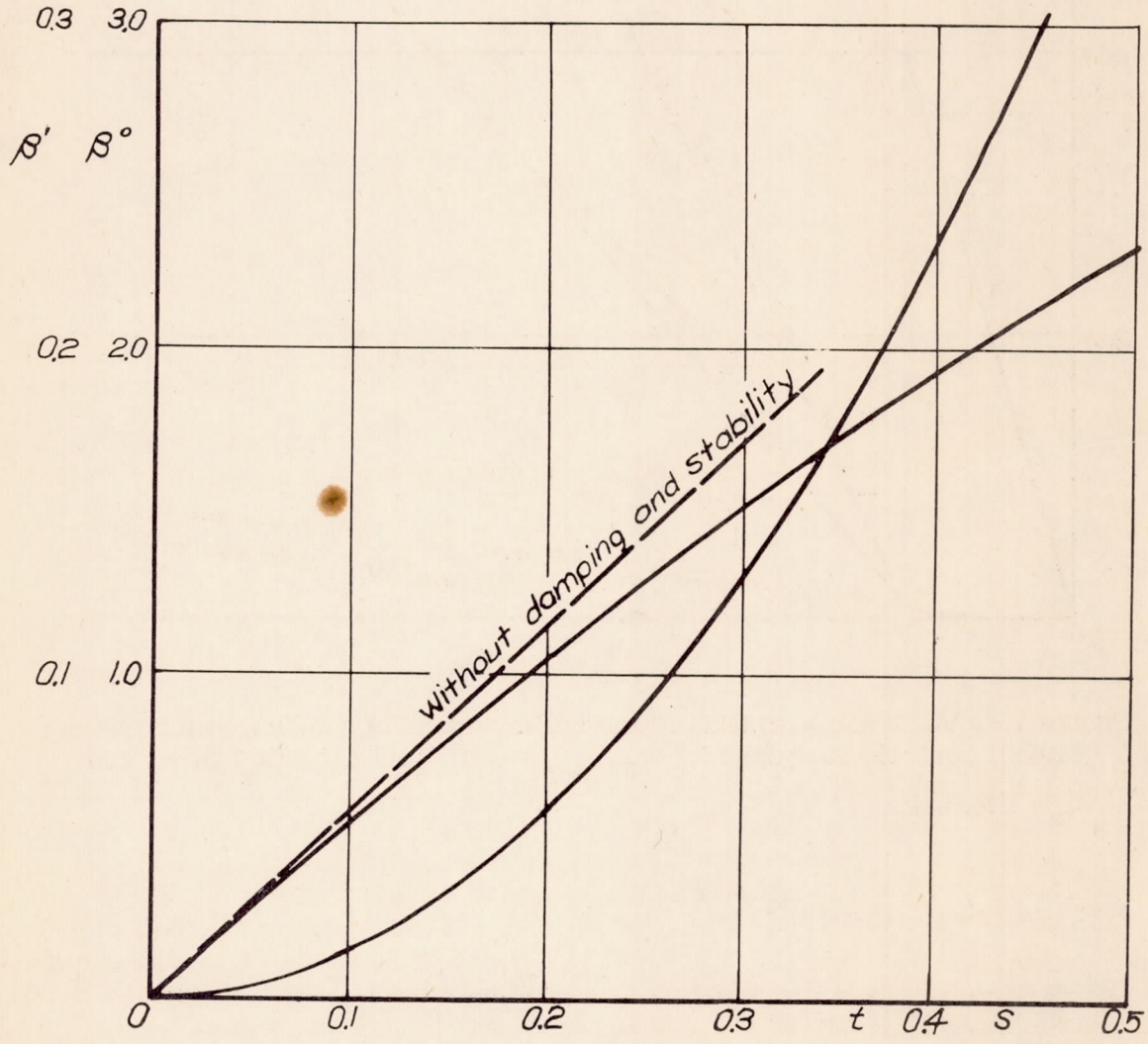

Figure 3.- Yawing motion for abrupt onset of the solid spoiler.

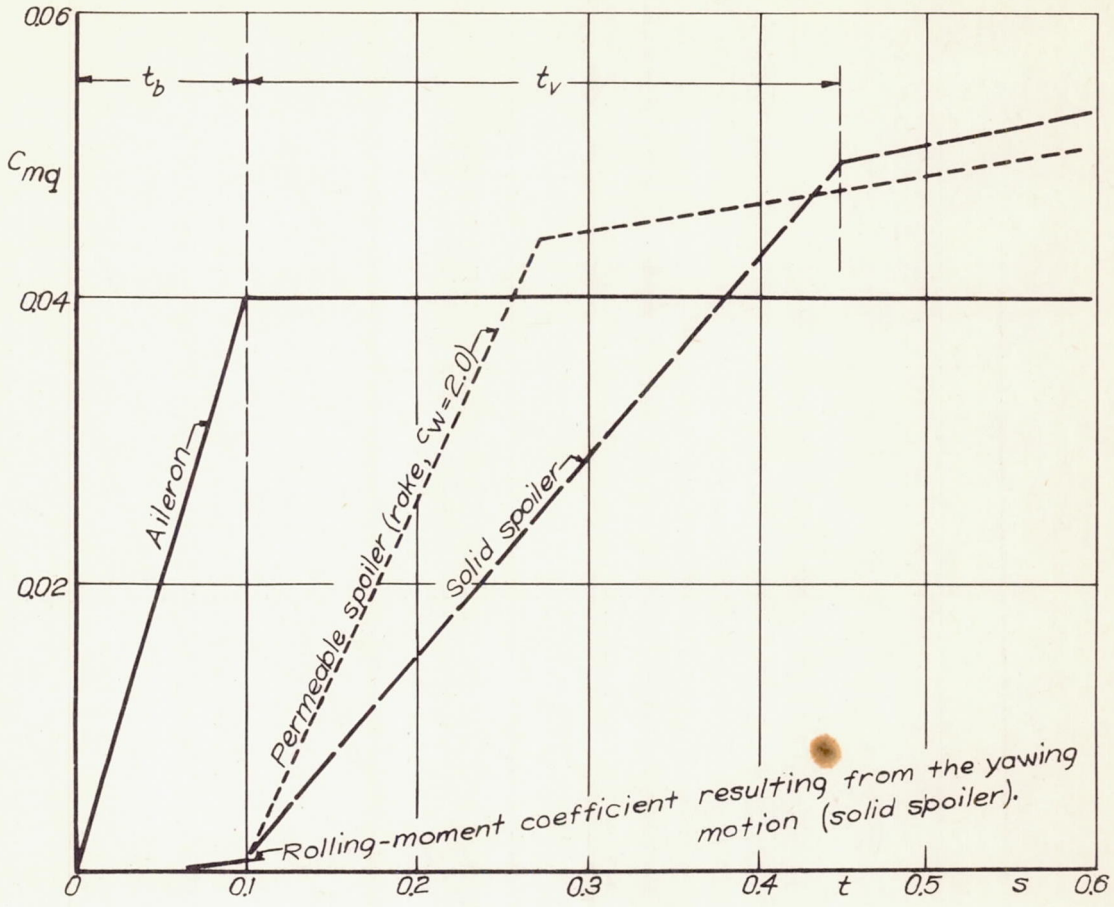

Figure 4.- Variation with time of the rolling-moment coefficient for three lateral controls equalized to $c_{mp_{stat}} = 0.04$, t_b = actuation time, and t_v = time lag.

$$C_{mq} = 100\, c_{mq};\quad C_{mq} = 1.56\, \bar{\varphi}'' + 6.4\, \bar{\varphi}'$$

$t = 1/20$ (s)

t	$C_{\overline{mq}}$	$\bar{\varphi}''$	$\Delta\varphi'$	φ'	$\bar{\varphi}'$	$\Delta\varphi$	φ	φ^o	Control
0+1/20	1.0	0.58	0.029	0.029	0.014	0.0007	0.0007	0.04	0.905 + 0.093 = 0.998
2/20	3.0	1.63	.081	.110	.070	.0035	.0042	.24	2.54 + .45 = 2.99
3/20	4.0	1.91	.095	.205	.157	.0078	.0120	.69	2.98 + 1.01 = 3.99
4/20	4.0	1.60	.080	.285	.245	.0122	.0242	1.39	2.50 + 1.57 = 4.07
5/20	4.0	1.30	.065	.350	.317	.0158	.0400	2.30	2.02 + 2.02 = 4.04
6/20	4.0	1.00	.050	.400	.375	.0187	.0587	3.36	1.56 + 2.40 = 3.96
7/20	4.0	.83	.041	.441	.421	.0210	.0797	4.56	1.29 + 2.70 = 3.99
8/20	4.0	.65	.032	.473	.457	.0228	.1025	5.87	1.01 + 2.93 = 3.94

$$\Delta\varphi' = \bar{\varphi}''\,\Delta t;\quad \varphi' = \Delta\varphi'_{(n)} + \varphi'_{(n-1)};\quad \bar{\varphi}' = \frac{\varphi'(n) + \varphi'(n-1)}{2} \quad \text{.....}$$

Figure 5.- Sample of the stepwise integration of the equation of the rolling motion (aileron).

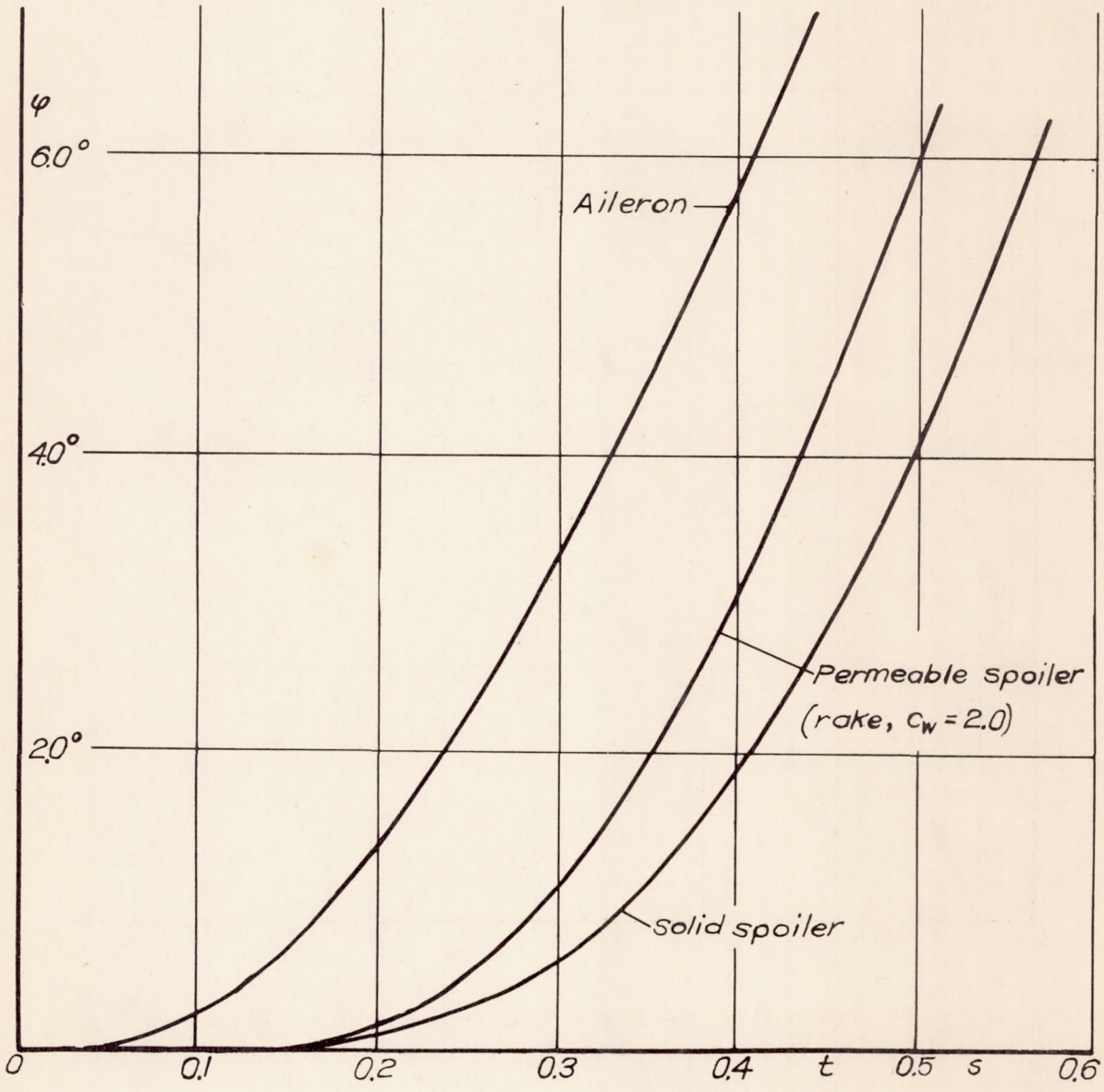

Figure 6.- Variation with time of the rolling angle for three different lateral controls.

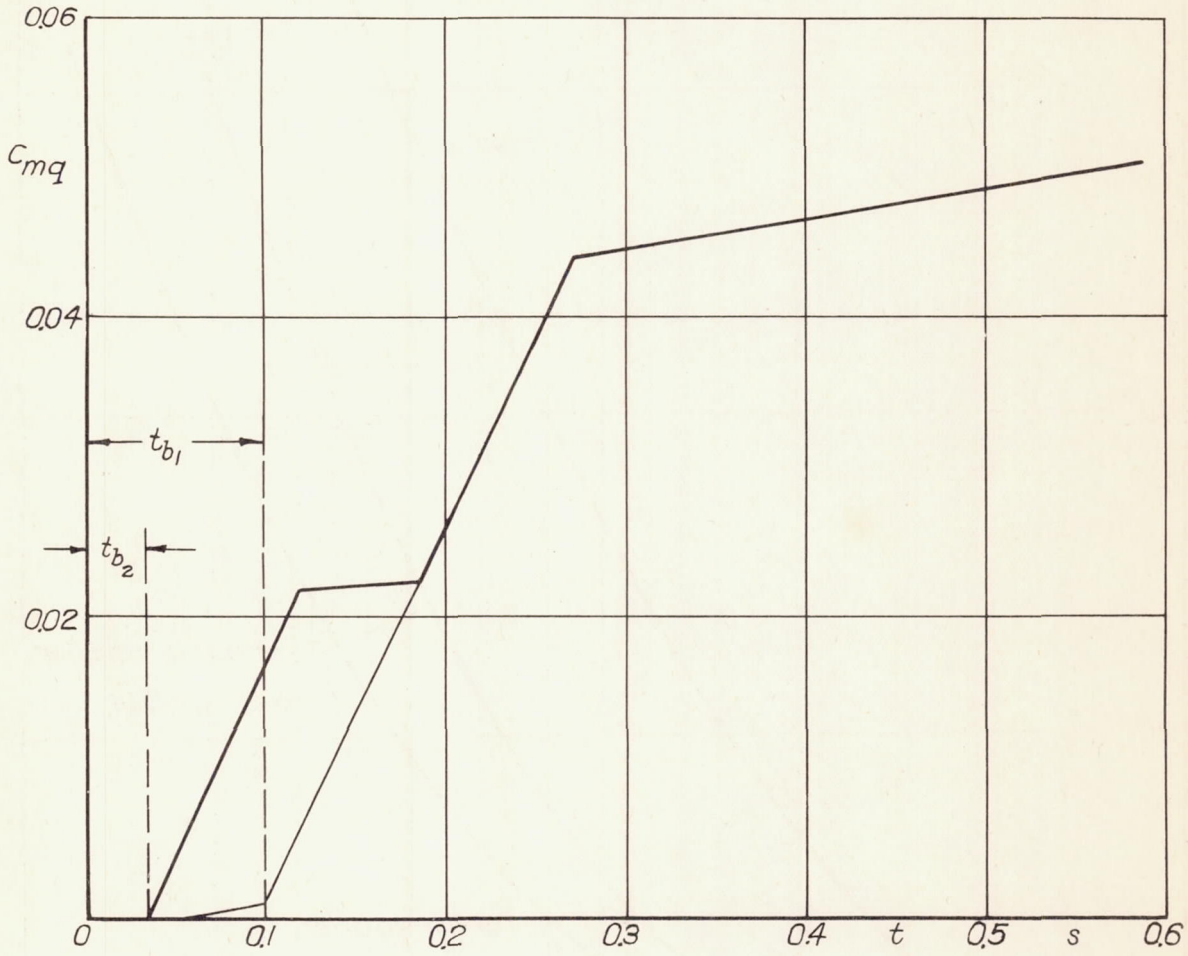

Figure 7.- Variation with time of the rolling-moment coefficient for mechanical and aerodynamic lead; t_b = actuation time, t_{b_2}/t_{b_1} = 1/3, c_{w1} = 2.0, c_{w2} = 0.66.

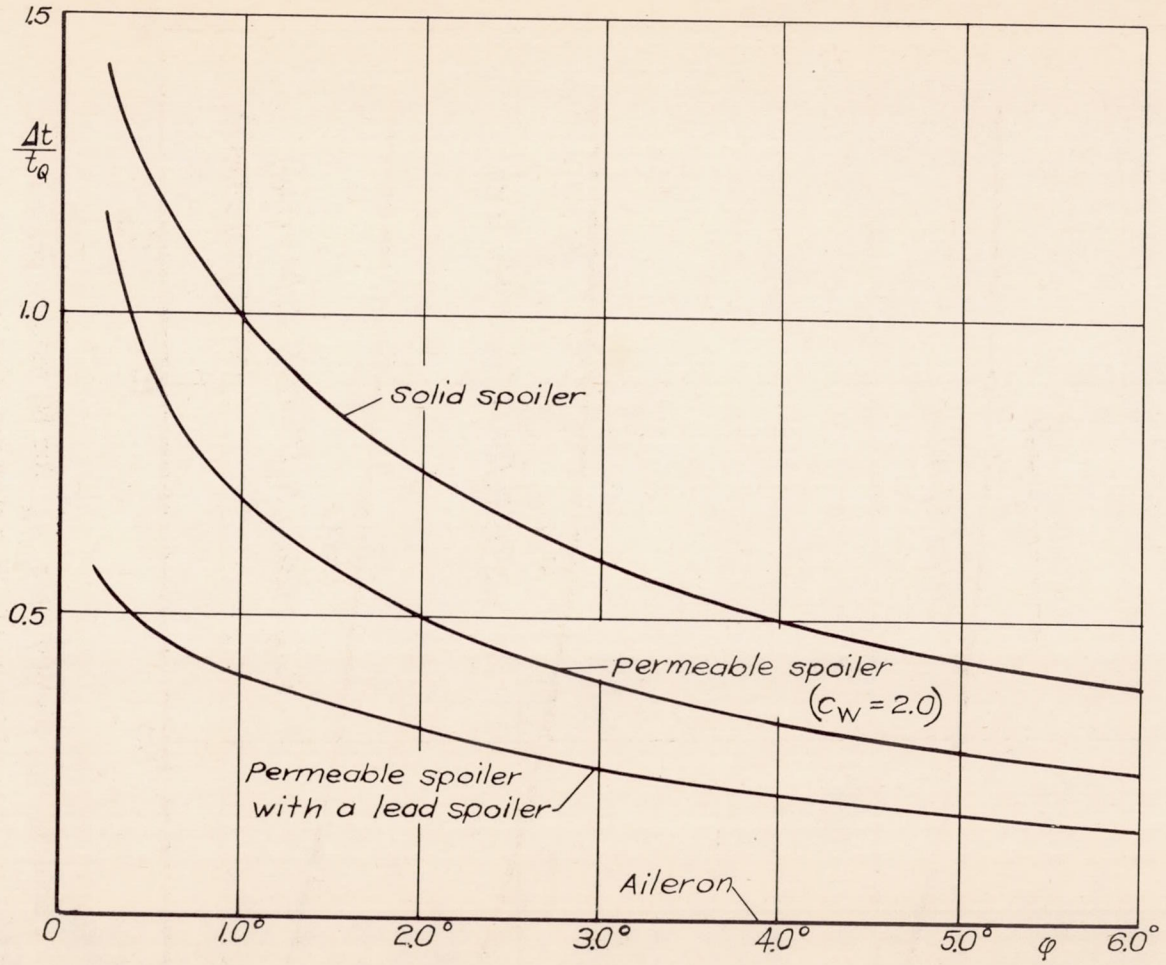

Figure 8.- Ratio $\Delta t/t_Q$ as a function of the rolling angle for the various controls. (The significance of $\Delta t/t_Q$ may be visualized from fig. 1.)

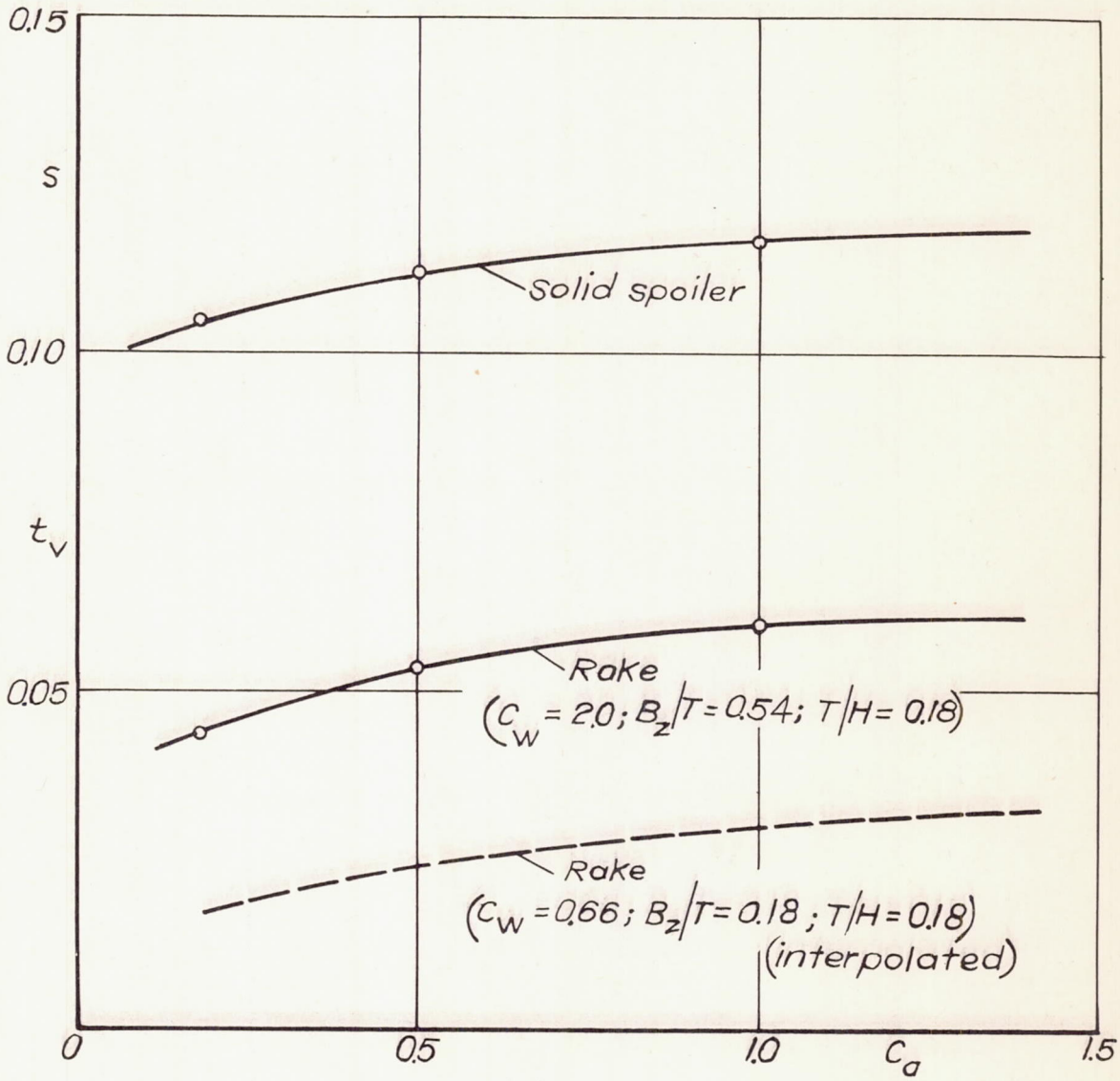

Figure 9.- Time lag t_v plotted over c_a for 50 meters per second velocity of the blower flow and 0.77 meter mean wing chord at the location of the spoiler for solid spoiler and two rakes of different permeability; B_z = tooth width; T = tooth spacing; H = tooth height.

PART III. FLIGHT TESTS IN THE LATERAL CONTROL BY SPOILERS ON THE AIRPLANE MODEL FIESELER FI 156

By C. G. Esche

Abstract: New lateral controls were investigated and compared with the aileron in flight tests on the airplane Fieseler Fi 156. Dynamic pressure, static pressure, angles of attack and of sideslip, and the variation with time of the bank, the rolling acceleration, and the aileron deflection were measured. The measurements permitted the determination of the time lags and the rolling moments of the individual lateral controls investigated. The measuring results are plotted over c_a in comparative representation and discussed.

Outline:

I. INTRODUCTION (SURVEY AND PRESENT STATE OF LATERAL-CONTROL INVESTIGATIONS)
II. TEST SETUP AND PERFORMANCE
III. MEASURING RESULTS AND DISCUSSION
(1) Time Lags
(2) Rolling Moments
IV. SUMMARY
V. REFERENCES

I. INTRODUCTION (SURVEY AND PRESENT STATE OF LATERAL-CONTROL INVESTIGATIONS)

Since the ailerons customary at present show certain defects which will, before long, make these lateral controls altogether useless, investigations with new lateral controls in flight by spoilers were carried out at the DVL.

The various disadvantages of the usual lateral controls and the advantages of the spoilers have been enumerated before (reference 1). The disadvantages of the spoilers which were noticeable in the first flight tests (references 2 and 3) and needed to be eliminated, were the lag in the rolling motion and excessive positive yawing moments. (Below, we shall denote the yawing moment of a lateral control as positive when it turns the wing - which is rolling downward due to aileron deflection - back about the vertical axis of the airplane as well.) The time lag at the start of the rolling motion amounted only

to fractions of a second (0.2 to 0.4s). However, this peculiarity of the spoiler easily led to over-control on the part of the pilot if the airplane was to be maintained in rectilinear flight in gusty weather; this was uncomfortable, particularly for take-off and landing. Furthermore, the lag in the rolling motion and the large yawing moments together made it impossible to perform coordinated smooth turns.

Wind tunnel measurements (reference 1) and further flight tests, with the model Messerschmitt M 27 (reference 3), for their confirmation had been carried out at the DVL in order to eliminate these disadvantages and to attain systematic data for the applicability of spoilers as lateral controls. The following recognized facts were the result of these tests.

The most favorable rearward position of the spoiler is at 0.20t, counted from the leading edge of the wing. Further shifting of the spoiler toward the rear produces, it is true, a reduction in time lag, but also rolling moments of insufficient magnitude. The most favorable spoiler height is (according to the tunnel tests) for solid spoilers 7 percent of the wing chord; for permeable spoilers, in contrast, an increase in rolling moment cannot be expected if the spoiler is deflected higher than 5 percent of the wing chord. The type of deflection - whether the spoiler is deflected in or against flight direction or whether it is extended vertically to the wing surface - does not noticeably affect the time lags. Nor did the deflection angle ζ_u (which for the flight tests lay between $\zeta_u = 50^\circ$ and 90°) cause a change of the time lags in the flight tests. In contrast, a reduction of the rolling moment by about 25 percent takes place when the spoiler deflection is decreased from $\zeta_u = 90^\circ$ to $\zeta_u = 60^\circ$.

Only application of screens permeable to air (as were suggested by M. Kramer for the investigation by the DVL) reduced the time lags. The more permeable the spoiler, the smaller the time lag. Of course, the permeability could not be increased arbitrarily since with increasing permeability the rolling effectiveness decreased more and more. According to the tunnel results, screens of about 50 percent solidity ($c_{ws} \approx 1.2$, determined from the pressure drop in the pipe) were most favorable. They produced in flight tests for smaller time lags (referred to the values of the solid spoiler) still sufficient rolling moments. Simultaneously, the screens yielded a sufficient reduction of the yawing moments.

Since the screens had proved in practical flight operation to be of little use (clogging of the grid, deformation, rough surface), still other types of permeable spoilers were investigated in the tunnel. It was shown that rakes of a certain tooth width B_z and spacing T, the

applicability of which in practice had seemed rather certain, were with respect to time lags and rolling effectiveness, no better than screens.

The flight tests described below were made for the purpose of confirming these regularities and results found in tunnel tests.

II. TEST SETUP AND PERFORMANCE

A special construction of the model Fieseler Fi 156 "Storch" (fig. 1) served as test carrier. The Storch is an externally braced high-wing monoplane with untwisted rectangular wing without sweepback. The angle of dihedral is $\nu = +45'$, but may be increased to $\nu = +3^{\circ}$. In standard construction, the wing has a slotted slat along its entire leading edge. During the flight tests with the spoiler control, the slot between slat and main wing was sealed so that a new wing profile resulted. The position of the center of gravity during the measurements was $0.367l$ to the rear of the leading edge of the wing.

Spoilers were provided on both wings, on the suction side as well as on the pressure side, at $0.21l$, $0.42l$, and $0.63l$ rearward position counted from the leading edge, always referred to the new profile originated by sealing the slat slot. The spoilers extended on each wing over $0.38s$ ($s = b/2$, cf. fig. 1) and could be deflected singly as well as jointly. Thus, it was possible to investigate several spoilers, arranged one behind the other, as well as to deflect simultaneously spoilers on the suction side of one wing and on the pressure side of the other. The spoilers were pushed out from the wing vertically to the wing chord. They moved on a circular path lying in the direction of the transverse axis so that they shifted slightly laterally as well when extended.

After the most favorable construction type (regarding permeability and spacing) for the spoiler in front had been found, it was combined with a lead spoiler (cf. fig. 2) according to the suggestion of M. Kramer (reference 4). The lead spoiler there is a rake of considerably higher permeability which combines both a rolling moment (though only a small one) and lesser time lag. In the test model of the Fi 156, it is pivoted in front of the main spoiler and is lifted up by this spoiler so that it attains its full deflection (5 percent l) when the main spoiler has been extended only to about 1/3 of its extension path. The lead spoiler has the purpose of reducing the aerodynamic as well as the mechanical lag. Moreover, it provides a desirable gradation of the course of the rolling moment over the control path.

All arrangements (spoilers as well as ailerons) were investigated for landing flap deflections of 0° and 40°. A coupling interspaced in the aileron linkage which could be operated in flight from the pilot's seat permitted switching over from aileron to spoiler as desired. There was always only one lateral control usable while the other was blocked in zero position. The separate arrangements investigated are compiled in table 1.

The measuring procedure was the same for all flight tests. Out of horizontal rectilinear flight a rolling motion (in all tests to the right) was initiated by sudden full aileron deflection; following, all control surfaces were held fixed until a bank of $\varphi \cong 60^{\circ}$ to 80° was attained. The aileron control times were, on the average, around $t_s = 0.08$ second. The measurements comprised the entire velocity range ($q = 20$ to 180 kg/m^2, $c_a = 0.3$ to 2.8). Dynamic pressure, static pressure, angle of attack, and angle of sideslip were measured by means of a Prandtl tube and angular pressure tube, respectively, and plotted by a DVL double recorder. The measuring accuracy of the devices corresponds to that described in FB 929 (reference 5). The dynamic-pressure calibration was made according to the approved method with differential-connection probe and total-pressure device.

Furthermore, a Sperry horizon, a stop watch with 3s rotation, and the reading of the spoiler deflection were filmed with a Siemens narrow-film camera. Observation of the Sperry horizon formed the basis for the determination of the lag in the rolling motion and of its further course.

Following, a distinction is made between two time lags (fig. 3). The time-lag definition (the obvious selection for a flight test) is: T_v = time interval from beginning of the spoiler deflection to the onset of the rolling motion perceptible on the Sperry horizon. It must be noted that the lateral controls investigated must show equal aileron control time if their time lags are to be compared in this manner. In the flight tests made with the model M 27 and Fi 156, compared below, this was the case.

In order to be able to compare, on the other hand, the tunnel results with those of the flight tests, we had to ascertain for the separate spoiler arrangements also the time lags as determined in the tunnel tests. In the tunnel, the time lag t_v was fixed as the time interval from the attainment of full spoiler deflection to the setting in of the full static rolling moment. The different modes of notation may be clearly seen from figure 3.

The static rolling moment of the lateral control L_Q results from the equation of the mass and air force moments about the longitudinal axis

$$J_x \frac{d\omega_x}{dt} - (J_y - J_z)\,\omega_y\omega_z = L_Q + L_{\omega_x} + L_{\omega_z} + L_\beta$$

Wherein:

L_Q = the static rolling moment of the lateral control

L_{ω_x} = the damping in roll

L_{ω_z} = the rolling moment due to yaw

L_β = the rolling moment due to side slip

The gyroscopic moment

$$(J_y - J_z)\,\omega_y\omega_z$$

and the rolling moment due to yaw L_{ω_z} are very small compared to the other contributions of the rolling moment and may be neglected. The moment of inertia about the longitudinal axis is according to the specification of the Fieseler Flugzeugbau and after consideration of the additional masses placed in the wing (due to spoiler and instrument installation)

$$J_x = 500 \text{ mkg s}^2$$

The angular acceleration was measured by means of a device developed in the DVL (reference 6). For the damping-in-roll, one may calculate according to Multhopp:

$$c_{l_x} = \frac{\partial c_L}{\partial \frac{\omega_x s}{v}} = 1.1 \quad \text{(for the rectangular wing at an aspect ratio of } \Lambda = 7.22\text{)}$$

Thus, the moment coefficient of damping-in-roll for the smooth wing will be

$$c_{L_{\omega_x}} = 1.1 \frac{\omega_x s}{v}$$

It must be taken into consideration that the deflection of a spoiler reduces the damping-in-roll of the wing. The tunnel measurements (reference 1) resulted for both the solid and the permeable spoiler, for spoiler deflection on one wing panel in a reduction of the c_a' by 20 percent. For the model Fi 156, one may, on the average, expect - in spite of the somewhat differing span portions covered by the spoilers - a reduction of the damping-in-roll by 20 percent.

In order to take into account the influence of the rolling moment due to sideslip, the increase of the rolling moment L_β with the angle of sideslip β was determined according to a method formerly employed by the DVL (reference 7).

The result was

$$\frac{\partial c_L}{\partial \beta} = 0.2$$

in the normal flight range ($c_a = 0.4 - 1.0$) for landing-flap deflection $\eta_k = 0^o$ and lateral control in zero position. Thus, one obtains

$$c_{L_\beta} = \frac{\partial c_L}{\partial \beta}\beta = 0.2\bar{\beta}$$

under the assumption that the flow conditions which vary due to spoiler deflection effect the rolling moment due to sideslip less than the damping-in-roll and that the two effects will balance each other.

From the above equation of the rolling moments there results, with the separate neglections taken into consideration

$$c_{L_Q} = \frac{J_x \frac{d\omega_x}{dt}}{qFs} + c_{L_{\omega_x}} - c_{L_\beta}$$

$$c_{L_Q} = \frac{J_x \frac{d\omega_x}{dt}}{qFs} + 1.1\,\frac{\omega_x s}{v}\,[1] - 0.2\bar{\beta}$$

The basic trend of the individual rolling-moment coefficients superimposed is shown in figure 4.

---

[1] For spoiler $c_{L_{\omega_x}} = 0.8\,\frac{\omega_x s}{v}$

III. MEASURING RESULTS AND DISCUSSION

1. Time Lags:

Evaluation of the Sperry horizon measurements permitted first the determination of the time lags T_v (from the beginning of the aileron deflection to the onset of the rolling motion). For the individual arrangements investigated, the time lags T_v have been plotted against c_a in figures 5 to 8. Since all measurements were started in rectilinear flight, c_a could be determined from $G = c_a qF$.

The curves shown in figure 5 which represent the course of the time lag T_v over c_a are averaged from a great number of measuring points. The variation of the measuring points was ± 0.03 second. Thus, strips of greater or smaller width result for the individual arrangements investigated which frequently overlap, particularly for the various rakes, and would present a confused picture. Thus, the comparison is made between the mean-value curves in figures 5 to 8.

Figure 5 shows the time lags measured in flight for the aileron, for the solid spoiler (permeability $D = 0$), and for two rakes of different permeability. The time lags of the spoilers increase with c_a. Corresponding to their dependence on the velocity, the curves of the lag over c_a must be, in theory, parabolas. With decreasing lift coefficients, the lags decrease quadratically. The reduction in time lag can be recognized clearly when rake-type spoilers of greater permeability are used.

The measuring series on the aileron showed an onset of the rolling effectiveness with the aileron deflection almost free from time lag. For the aileron, the rolling motion starts, on the average, 0.05 second after the beginning of the aileron deflection, thus still during the aileron control time. Directly at the end of the aileron control time, the full rolling moment is reached.

After the permeability $D = 0.5$ had been chosen as the one most favorable for spoilers (with regard to the attainment of sufficient rolling moments), the problem was to find for it the right rake spacing ratio. Figure 6 shows, over c_a, the time lags for three rakes of equal permeability and the same rearward position $0.21l$, but of different spacings, thus different tooth widths (B_z = 4, 10, and 15mm). The values for the solid spoiler and the aileron are again plotted for comparison. In figure 7, the influence of the rake spacing is shown once more, this time at a c_a-value of 0.6. The time lags (values taken from flight tests as well as from tunnel measurements) are plotted

against the ratio of spoiler spacing to spoiler height (T/H). The essential fact is that both tunnel and flight measurement have their optimum at the same ratio (T/H).

This shows how the lag is dependent on the turbulence produced. Thus, the rake must have a certain tooth width (referred to the wing chord). The best of the three rakes compared here has the following dimensions:

Tooth height $H = 5$ percent l

Tooth width $B_z = 0.5$ percent l

Tooth spacing $T = 1$ percent l

Finally, the lag can be reduced - as mentioned at the beginning of this report - by further rearward position (reference 8). Measurements with a solid spoiler at 63 percent l rearward position showed, for small c_a-values, lags reduced by two-thirds and, for large c_a-values, lags reduced by almost half the original values. Figure 8 (bottom, right) shows the basic course of the reduction of the time lag with the rearward position of the spoiler.

The time lags shown here have all been determined on one and the same test carrier. If one now wants to transfer the time lags to another model or to compare the existing flight measurements with the tunnel results, one has to consider - corresponding to the character of the spoiler - the new wing chord at which the spoiler acts and the new flight velocity, thus

$$T_{v_{new}} = T_{v_{156}} \frac{l_{new}\, v_{156}}{l_{156}\, v_{new}}$$

since the time lag is directly proportional to the wing chord and inversely proportional to the flight velocity.

In this manner, the results obtained with the M27 and in the tunnel could be transferred to Fi 156 conditions. The comparison between the measuring results obtained with the two models M27 and Fi 156 shows good agreement (cf. fig. 5).

The numerical values of the lags for the "Storch" lie, with $T_v = 0.25$ to 0.35 second, still rather high in view of the fact that one quite generally tries - on the basis of practical flying experience - to avoid, as far as possible, time lags beyond 0.1 second. It must be noted that those lags are already maximum values. As a rule, the wing chord in the outer wing half (for trapezoidal construction type) probably will hardly exceed that of the "Storch" ($l_{Fi\ 156} = 2$m). Smaller

airplanes (pursuit planes) will probably have wing chords of only about half this magnitude so that the time lags then also would decrease by 50 percent. Finally, conditions improve with growing wing loading G/F since with it the velocities increase quadratically. Thus, one may expect, for instance, for the Me 109 (cf. fig. 9) time lags approximately three times as small since its wing loadings are, with G/F = 125 kilograms per meter^2, two and one-half times those of the "Storch" whereas the mean wing chord on the outer wing is, for the Me 109, only l_m = 1.40 meters. These values promise to be sufficient even for such a highly sensitive airplane as the Me 109. Figure 9 shows clearly the gain obtained; the 0.1 second limit is reached.

If, for certain airplanes (perhaps with greater wing chords) and for large c_a-values, the time lags should still be too high, there always remains the possibility of extending, aside from the rake in front, a second spoiler near the trailing edge of the wing. For a model provided with split flaps, the installation of such a second spoiler would probably not present any difficulties.

A comparison of two rakes with increasing and decreasing permeability along the spoiler height showed time lags of equal magnitude in both cases.

The measuring series with the lead spoiler did not yet produce a conclusive result since on the Fieseler Storch a lead spoiler could be installed only in a makeshift manner. Flight tests with another test carrier will yield information on this spoiler arrangement.

As to the time lags, it must be noted that they are reduced by the rolling moments due to sideslip and due to yaw of the spoiler. It has been pointed out before, (references 3 and 9), that the rolling moment due to sideslip may have an essential effect on the magnitude of the time lags, particularly in case of wing units with large amounts of dihedral. For the model Fi 156, the reduction in time lag caused by the yawing and sideslip motion is, in case of rakes, 0.01 to 0.02 second, and in case of a solid spoiler (corresponding to the more pronounced yawing motion) 0.02 to 0.03 second.

In order to make a comparison with the results of the tunnel measurements possible, the time lags t_v found in the tunnel, converted to the conditions of the Fi 156, have been plotted beside the flight test results in figure 10. The time lags found in flight tests are considerably larger than those measured in the tunnel. The difference between the results of these flight and tunnel measurements is probably partly motivated by the manner of the c_{L_Q} determinations. Since the variation with time of the static rolling moment of the lateral control was found from superposition of the separate contributions to the rolling moment, the c_{L_Q}- values are affected by all the errors

occurring in the determination of the single components. Errors occur in the differentiation of the rolling angle φ and in the estimation of the spoiler influence on the reduction of damping-in-roll, in the determination of the rolling moment due to sideslip and by neglection of the rolling-moment contributions connected with ω_z. For the c_{L_Q} determination, this method had to be followed since, as said above, only the resultant angular acceleration is measured in the flight test, and the static rolling moment of the lateral control can be found only by consideration of the separate rolling-moment contributions.

Although the time lags t_v measured in the tunnel and in flight, respectively, do not agree quantitatively, one still recognizes the fundamentally equal course of the time lags t_v over c_a. Furthermore, the comparison shows - and this is particularly important in practice - that the rake most favorable, according to the tunnel tests, proved to be the most advantageous arrangement for the flight tests as well.

Summarizing the results of the lag measurements briefly once more, one obtains the following recognized facts:

The time lags of spoilers increase with c_a; they are directly proportional to the wing chord and about inversely proportional to the flight velocity. They can be sufficiently reduced by means of permeable rakes (attention to be paid to the spacing ratio), and furthermore by means of spoilers lying near the trailing edge of the wing. Comparison of the tunnel results with those of the flight tests shows qualitative agreement.

2. Rolling Moments:

The variation of the maximum values of the rolling moment c_L* over c_a is represented in figures 11 and 12. Since these curves were determined from the rolling motion of the airplane measured in flight, they contain not only the static rolling moment of the respective lateral control (c_{L_Q}) but, in addition, the influences of the rolling moments due to yaw and to sideslip (c_{L_β}). The influence of the latter is discussed further. The curves of figures 11 and 12 also are averaged from a great number of measuring points, the dispersion of which is, on the average, $\Delta c_L \pm 0.05$. In agreement with the previous results of the tunnel and the M27 flight tests, the rolling-moment coefficients c_L* of the spoilers increase with c_a in the entire range investigated. In comparing the aileron rolling moments with those produced by spoiler deflection, one must take into consideration the fact that in the present tests the ailerons were deflected on both wings, the spoilers, however,

only on the right wing. In case of the spoiler, in contrast to the aileron, the rolling moment is therefore obtained by lift reduction on only one wing. Figure 11 shows the rolling moments of a rake with the permeability D = 0.5 to be about equivalent to those of a solid spoiler. Further increase in permeability produces a considerable reduction of rolling moment, as can be seen from the measuring series of the two other rakes (D = 0.67 and D = 0.82). The influence of the rake spacing can be recognized from a comparison of the two rakes with the spacings T = 8 millimeters and T = 20 millimeters

Figure 12 shows the decrease of rolling moment with increasing rearward position of the spoiler, and the rolling effectiveness of spoilers on the pressure side of the wing profile. One needs spoilers on the pressure side in order to have a lateral control still effective for upside-down flight. Originally these spoilers on the lower side were thought necessary for control of the excessive yawing moments. However, the flight tests showed that the yawing moments of the permeable spoilers are definitely no longer undesirably large. The yawing moments set in without lag. The supposition that spoilers on the lower side of the wing might have a lift-increasing effect and thus might produce an additional small favorable rolling moment was not confirmed by the flight test. Flaps on the pressure side will have a lift increasing effect only if they are located very far toward the rear. However, the unfavorable rolling moments of the spoilers on the lower side are so small that they are acceptable in view of acquiring in exchange a lateral control for upside-down flight.

In the Storch measurements, the spoilers extended over ~40 percent of the span. By increase of these span portions, the rolling effectiveness may be still further increased, within certain limits.

In order to take into consideration the influence of the rolling moment due to sideslip, the increase of the rolling moment L_β with the angle of sideslip β was determined. Since the spoiler deflection causes a yawing motion in the sense of the desired curve, the rolling moment due to sideslip improves the rolling effectiveness and must therefore be subtracted from the rolling moment (c_L*) in order to obtain the static rolling moment of the lateral control (c_{L_Q}) by itself. The rolling-moment coefficients c_{L_Q} thus determined are plotted over c_a for the most favorable rake and for the solid spoiler in figure 13. This figure shows that the static rolling moments for the most favorable rake lie even somewhat higher than for the impermeable spoiler. This finding confirms the results obtained in the tunnel with permeable spoilers. Only the fact that the solid spoiler is characterized by a larger yawing moment and thus also by a larger rolling moment due to sideslip than the rake-type spoiler makes it possible that in the

comparison of the rolling-moment coefficients c_L*, the solid spoiler appears better. As can be seen from figure 13, the influence of the rolling moment due to sideslip decreases with increasing c_a because the yawing moments attendant to the spoiler decrease with c_a.

For the aileron, in contrast, the rolling moment due to sideslip - corresponding to the yawing moment in reverse direction - takes effect in the unfavorable sense. The variation of the rolling-moment coefficients c_{L_Q} for large c_a-values for the aileron was estimated since in this c_a-range the rolling moment due to sideslip L_β could not be determined.

The mutual coaction of the initial time lag and the attainable rolling moment is shown in figures 14 and 15. There the variation of the measured rolling angle is plotted against time for two different c_a-values (c_a = 0.6 and 1.8). Whereas for medium c_a-values, the variations of the rolling motion caused by deflection of a solid spoiler or of a rake, respectively, are about the same, conditions change in favor of the rake in case of large lift coefficients.

IV. SUMMARY

On the airplane Fi 156 various lateral controls by spoilers were investigated and compared with the aileron and with spoilers tested previously on the model M27. The purpose of the measurements was to determine the time lags characterizing the different spoilers. Futhermore, the quantities measured yielded the rolling-moment coefficients of the various lateral controls.

The measuring procedure was as follows: For initial dynamic pressures which were different in each case (c_a = 0.3 to 2.8; q = 17 to 180 kg/m^2), a rolling motion was started by sudden lateral-control deflection, and the variation with time of the lateral-control deflection, the rolling angle, and the rolling accleration was measured as well as the dynamic pressure, the static pressure, and the angles of attack and of sideslip.

The measurements showed that it is always necessary to take into account, on principle, the dependence of the spoiler effect on the flight velocity and on the wing chord.

The time lag may be reduced by means of permeable rakes of a certain spacing ratio with a certain tooth width and, furthermore, by means of spoilers placed near the trailing edge of the wing.

The rolling effectiveness of the permeable spoiler is equivalent to that of a solid separation flap.

The yawing moments of appropriately chosen permeable rakes are about half those of solid spoilers. They take effect in the sense of a curve, not in the opposite sense as the yawing moments of ailerons.

On the other hand, it is still an unsolved problem whether and how far the spoiler affects the behavior of an airplane in case of large angles of attack. This problem will be clarified after further flight measurements with a test carrier which is suitable for this problem and which is now being prepared.

The measuring results of the flight tests as well as the judgments - based on "feel" - of different pilots lead to the opinion that the spoiler as lateral control is capable of development.

Translated by Mary L. Mahler
National Advisory Committee
For Aeronautics

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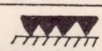
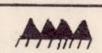
TABLE I

SPOILER ARRANGEMENTS INVESTIGATED

	Type of spoiler	Position		Spoiler height H		Tooth width B_z		Spacing T	$\frac{B_z}{T}$	$\frac{T}{H}$	Permeability = $\frac{\text{permeable area}}{\text{total area}}$
		on	at rearward position of	in portions of the wing chord	in millimeters	in portions of l	millimeters	millimeters			
1.	Solid spoiler	Suction side	0.21l	0.050l	100	--	--	--	--	--	0
2.	" "	"	0.63l	0.038l	75	--	--	--	--	--	0
3.	" "	Pressure side	0.21l	0.046l	90	--	--	--	--	--	0
4.	Rake	Suction side	" l	0.050l	100	0.0020l	4	8	0.50	0.08	0.50
5.	"	"	" l	" l	100	0.0051l	10	20	0.50	0.20	0.50
6.	"	"	" l	" l	100	0.0076l	15	30	0.50	0.30	0.50
7.	"	"	" l	" l	100	linearly variable		18	0.50	0.18	0.50
8.	"	"	" l	" l	100			18	0.50	0.18	0.50
9.	"	"	" l 0.63l	" l 0.038l	100 75	" --	 --	18 --	0.50 --	0.18 --	0.50 0
10.	"	"	0.21l	0.050l	100	0.0010l	2	6	0.33	0.06	0.67
11.	"	"	" l	" l	100	0.0018l	3.6	20	0.18	0.20	0.82
12.	Rake with lead spoiler	"	" l	" l	100	0.0051l 0.0018l	10 3.6	20 20	0.50 0.18	0.20 0.20	0.50 0.82
13.	Rake	Pressure side	" l	0.046l	90	0.0051l	10	20	0.50	0.22	0.50

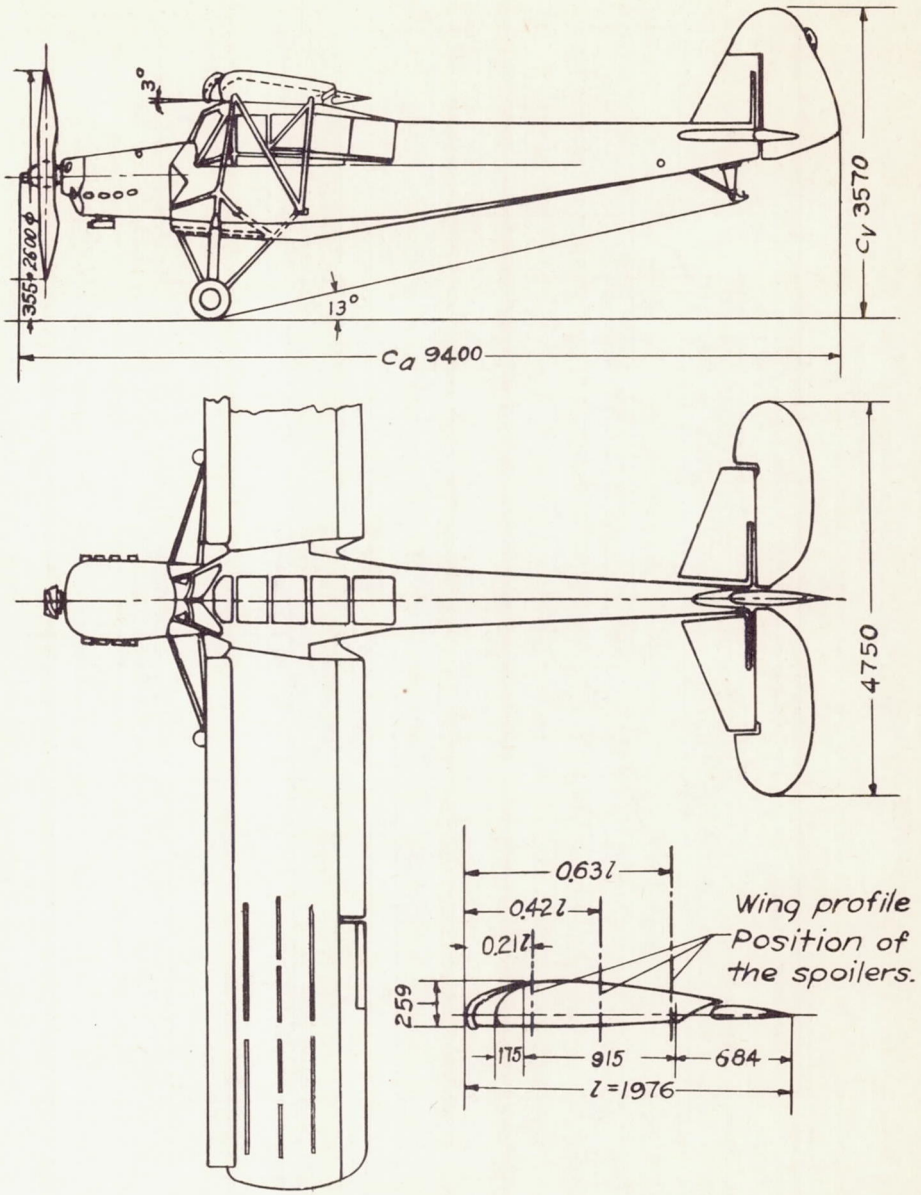


Figure 1.- Airplane Fieseler Fi 156. Data of the test carrier Fieseler Fi 156 "Storch."

Span	$2s = b = 14.25m$	Flying weight	$G = 1250$ kg
Wing chord	$l = 1.976m$	Wing loading	$G/F = 48$ kg/m^2
Aerodynamic surface	$F = 26m^2$	Power loading	$G/N = 5.25$ kg/hp
Aspect ratio	$\Lambda = 7.22$	Motor Argus Ar 10 C	$N = 240$ hp
Maximum thickness	$\delta_{max} = 0.267m$		
	$\frac{\delta_{max}}{l} = 0.135$		

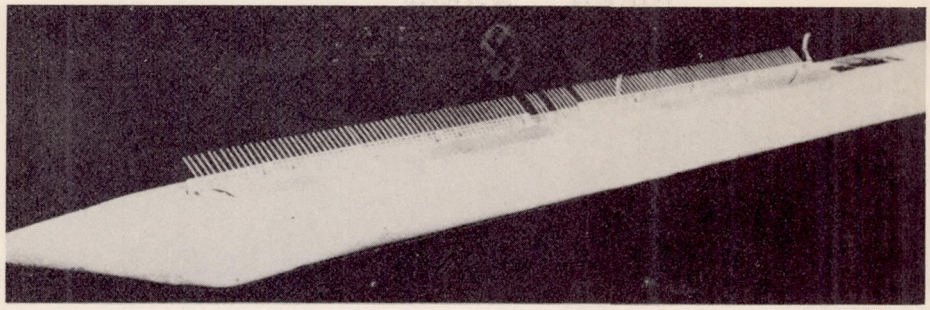


Figure 2.- Lead spoiler arrangement on the wing of the airplane Fi 156. In the photograph, the main spoiler has attained about 30 percent of its maximum deflection.

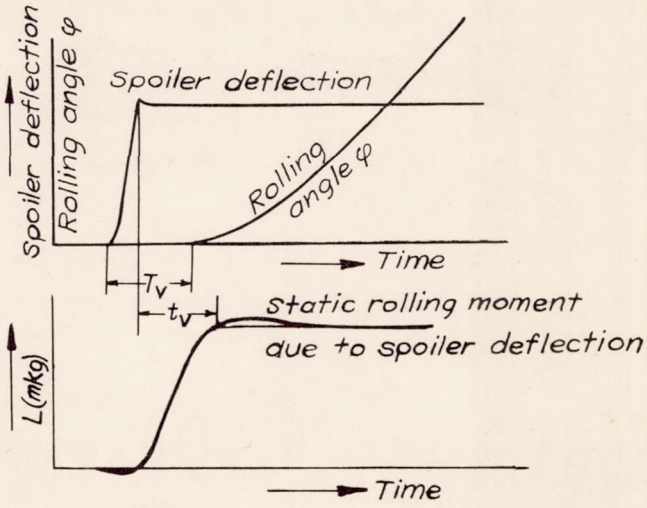


Figure 3.- Time lags T_V (flight test) and t_V (wind tunnel).

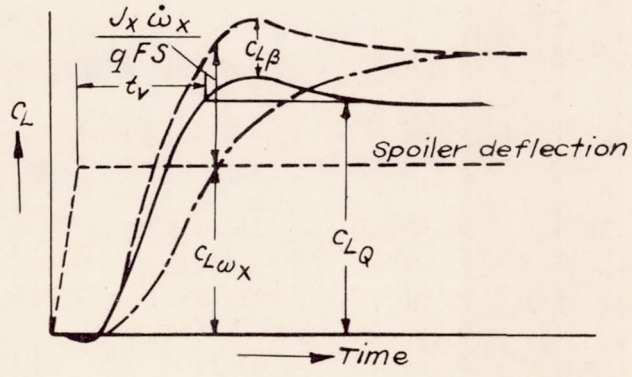


Figure 4.- Variation of the rolling moments plotted against the time for spoiler deflection. $c_{L_Q} = c_{L_{\omega_X}} + \frac{J_X \dot{\omega}_X}{qFs} - c_{L\beta}$.

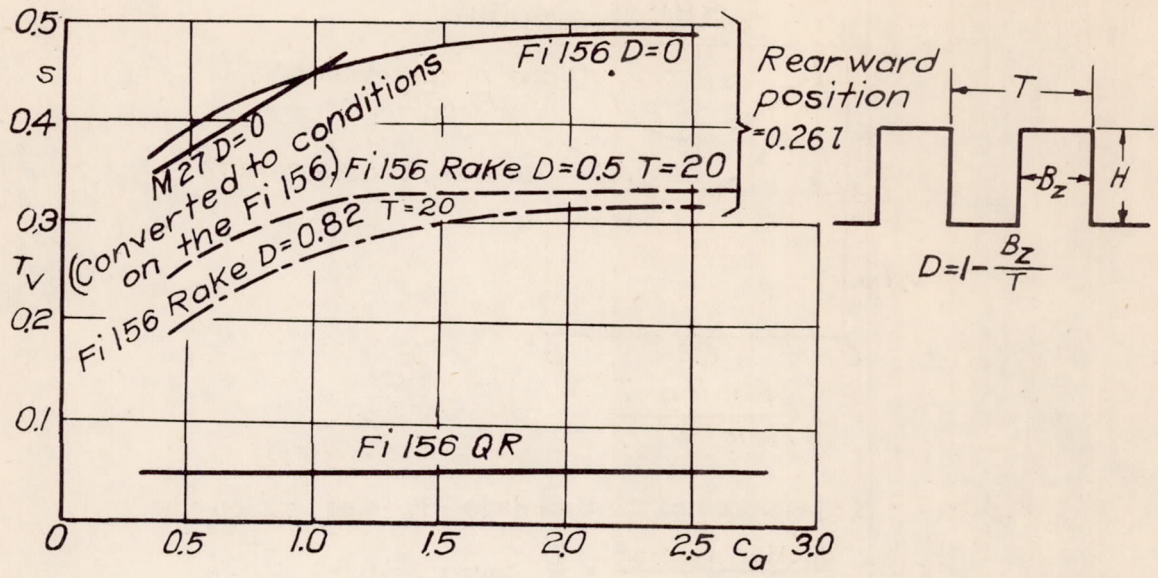


Figure 5.- Time lags T_V as a function of c_a for ailerons and for spoilers of various permeability, for 0.21l rearward position and 0.05l height of deflection.

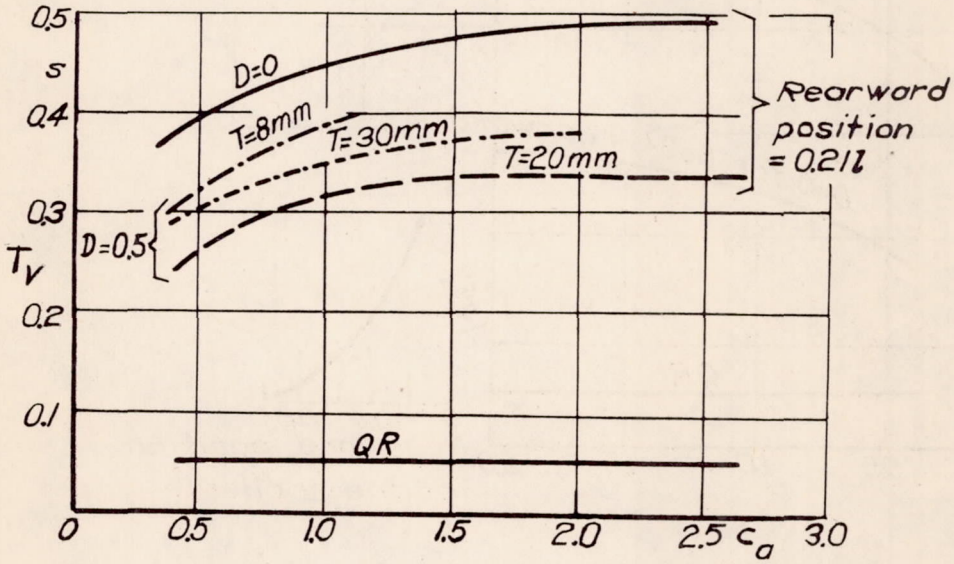


Figure 6.- Time lags T_V, measured on the airplane Fi 156, as a function of c_a for three rakes of different spacing T.

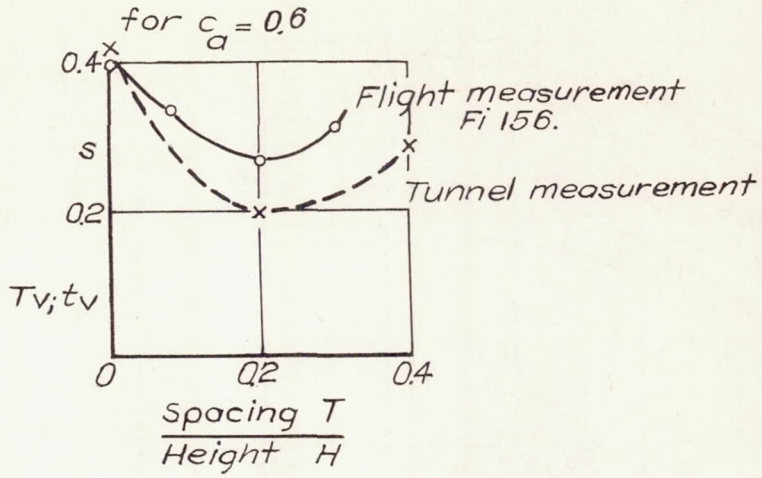


Figure 7.- Dependence of the time lags T_V and t_V on the ratio $\frac{\text{spoiler spacing}}{\text{spoiler height}} = \frac{T}{H}$ for $c_a = 0.6$.

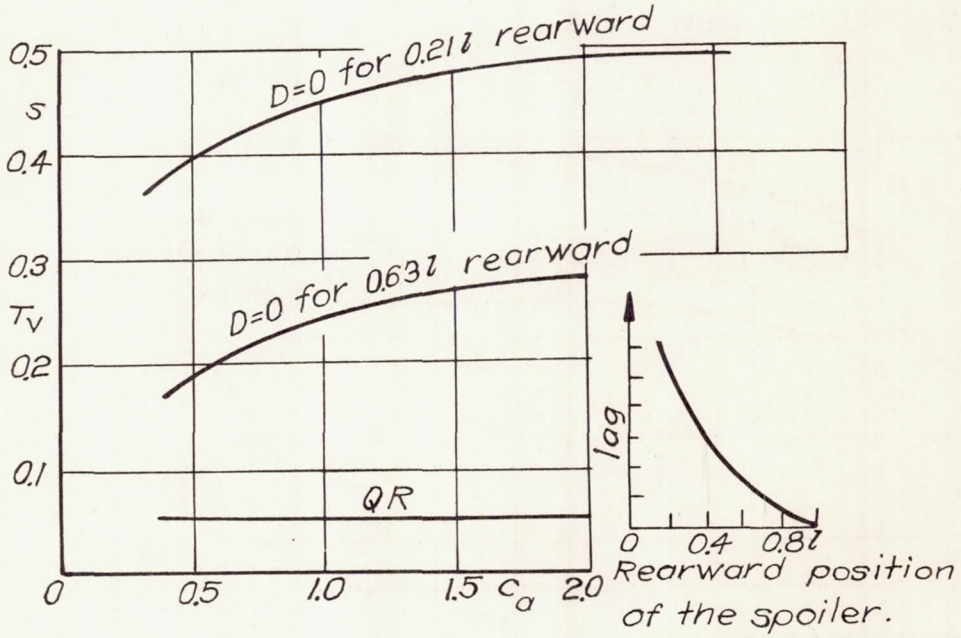


Figure 8.- Time lags T_V measured on the airplane Fi 156 for spoilers of different rearward position.

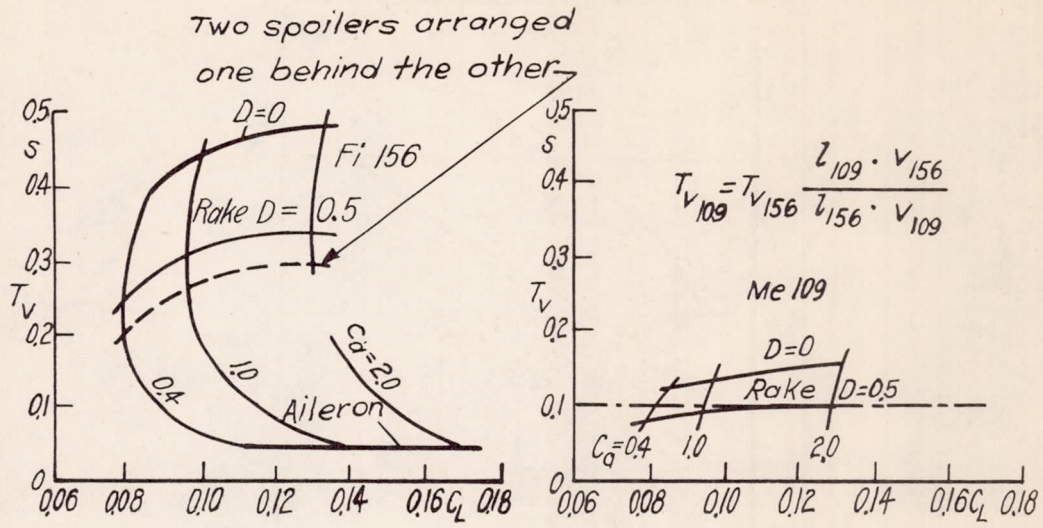


Figure 9.- Time lags T_V plotted against the rolling-moment coefficient c_L for c_a = 0.4, 1.0, and 2.0 for the airplanes Fi 156 and Bf 109.

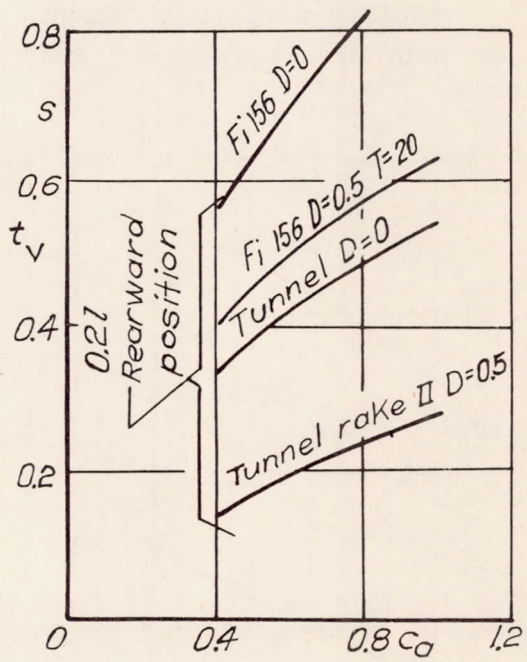


Figure 10.- Comparison of the time lags t_V obtained from tunnel and flight measurements for the solid spoiler (D = 0) and the rake (D = 0.5).

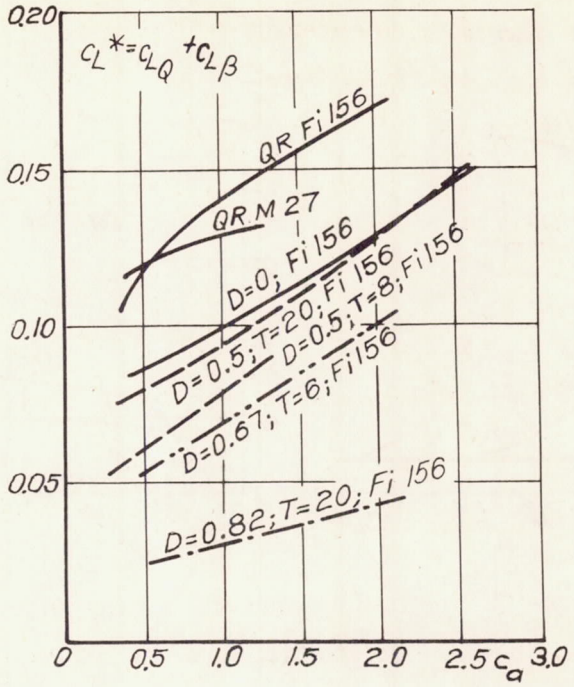


Figure 11.- Variation of the rolling-moment coefficients c_L^* for ailerons and spoilers of different permeability and spacing.

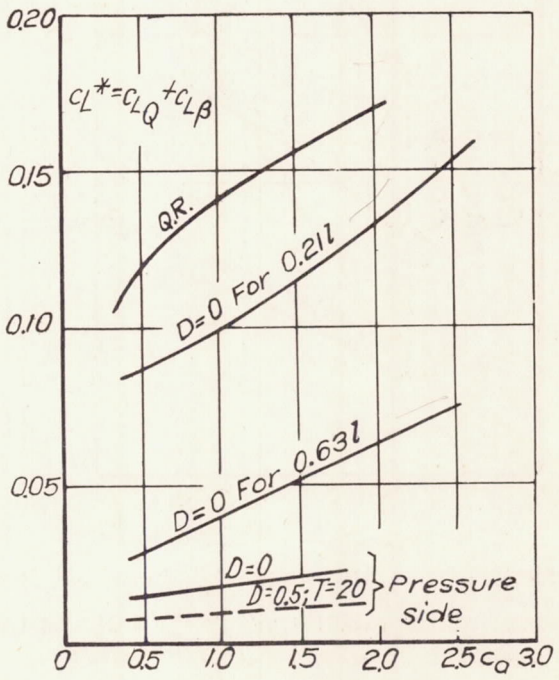


Figure 12.- Variation of the rolling-moment coefficients c_L^* measured on the airplane Fi 156 for spoilers of different rearward position and for spoilers at the lower side of the wing at 0.21l rearward position.

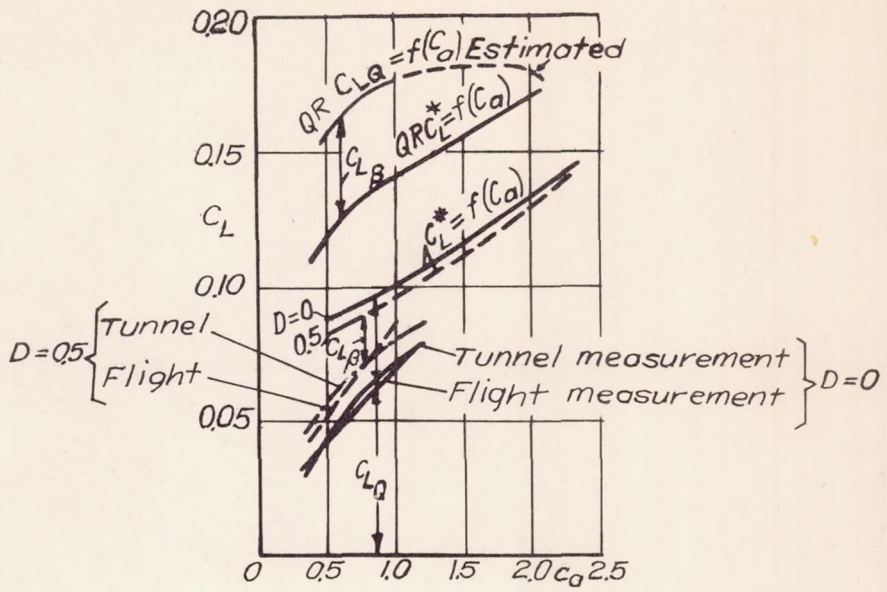


Figure 13.- Variation of the static rolling-moment coefficients c_{L_Q} for aileron and the spoilers (D = 0 and D = 0.5) plotted against c_a according to measurements on the airplane Fi 156.

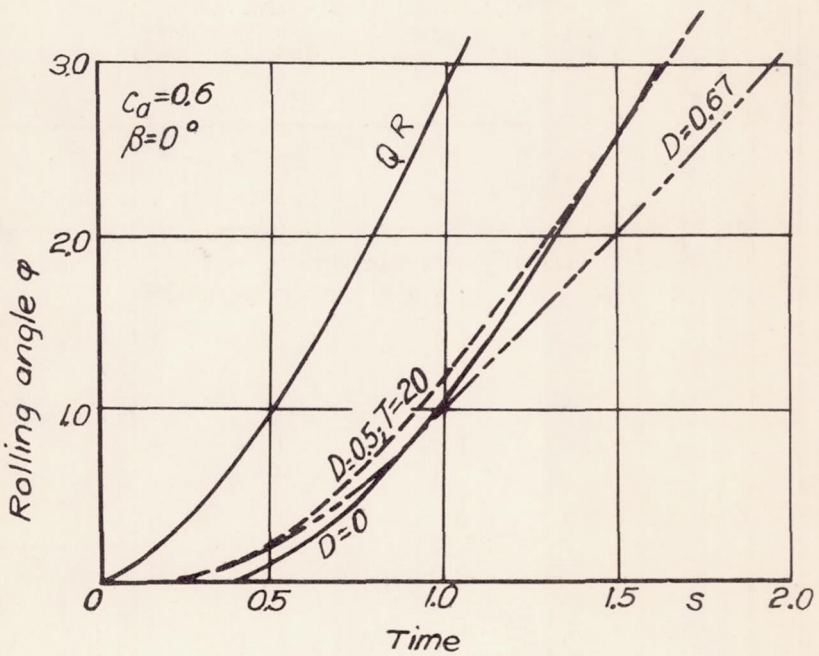


Figure 14.- Variation of the rolling angle φ plotted against time for aileron and for three spoilers of different permeability D for 0.21l rearward position on the airplane Fi 156 at c_a = 0.6 and landing-flap deflection $\eta_k = 0^\circ$.

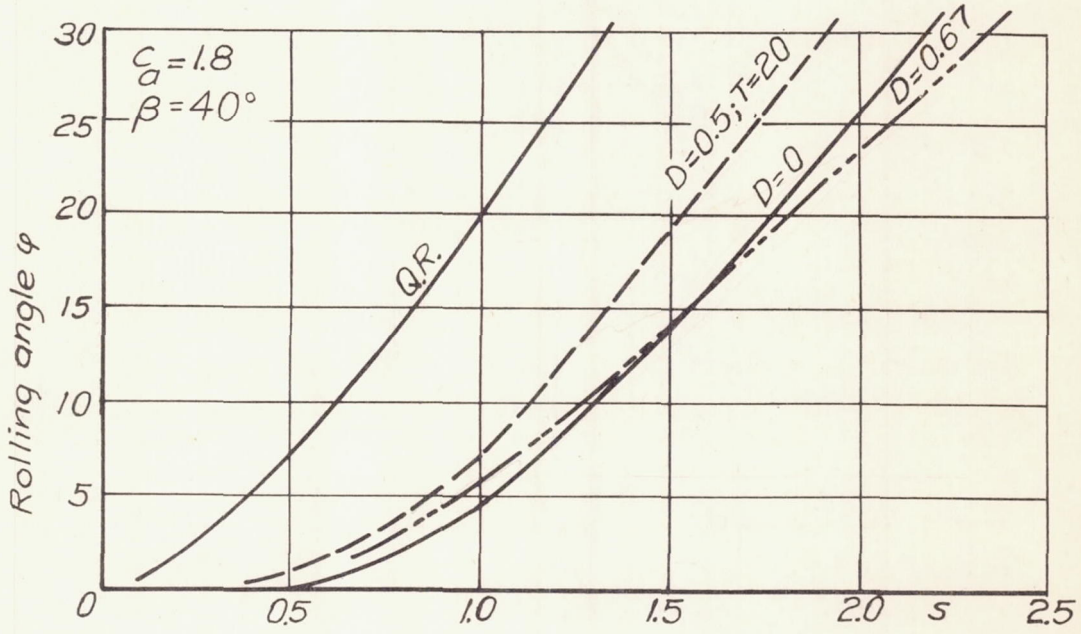


Figure 15.- Variation of the rolling angle φ plotted against time for aileron and for three spoilers of different permeability D for $0.21l$ rearward position on the airplane Fi 156 at $c_a = 1.8$ and landing-flap deflection $\eta_k = 40^\circ$.